University of Chicago

Argonne NATIONAL LABORATORY

Photon Detection

in Water and Scintillator Detectors

Matt Wetstein
Enrico Fermi Institute, University of Chicago

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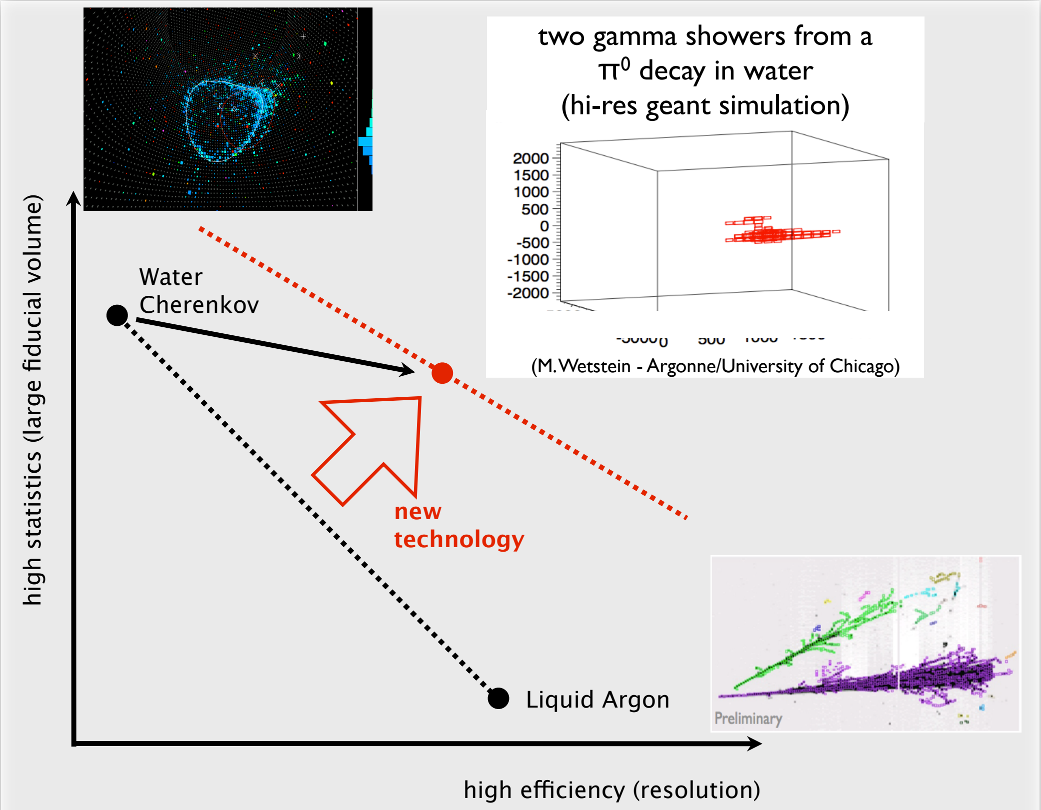
U.S. DEPARTMENT OF ENERGY

Introduction

- Photodetectors are a (~80 year old) staple of particle physics
- Photodetection plays and will continue to play critical role in neutrino detectors
- Next generation neutrino experiments are testing the limits of size and cost.
- Advancing photosensor technology is a high-impact way to change technological and economic trade offs



tradeoff curves of constant cost

Moving the Tech Forward

Improving how photosensors perform

- time resolution
- spatial granularity
- quantum efficiency/area coverage
- wavelength dependent response
- photon counting
- cost

Not only

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Moving the Tech Forward

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Improving how photosensors perform

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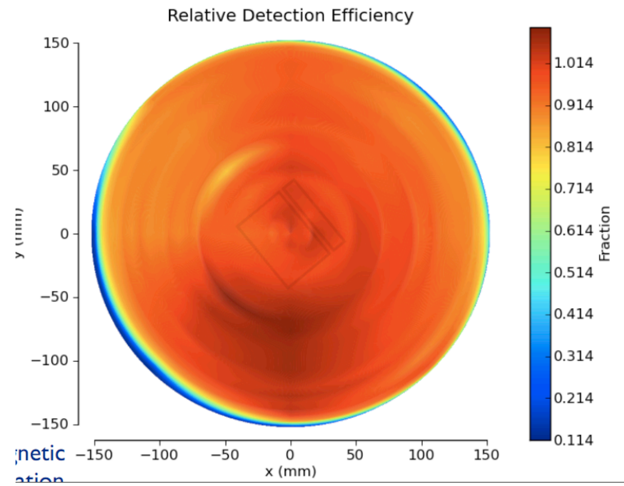
But also

Improving how photosensors are *used*

- light collection
- precision single photon likelihoods (optical TPC)
- dual Cherenkov-scintillation systems (ASDC/THEIA)
- optical imaging (reflective/refractive geometries)

Conventional PMTs

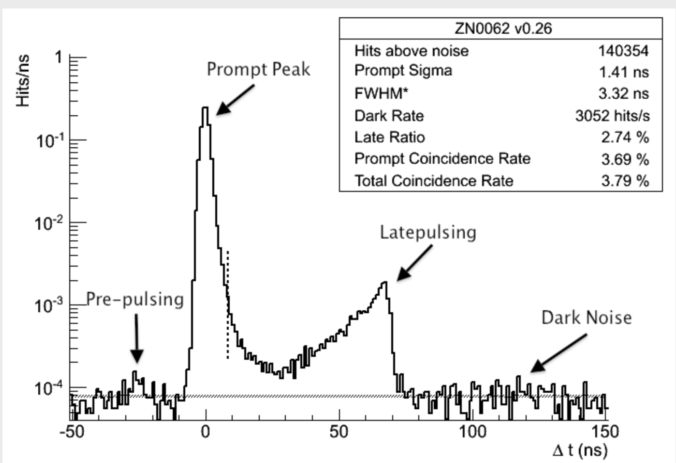


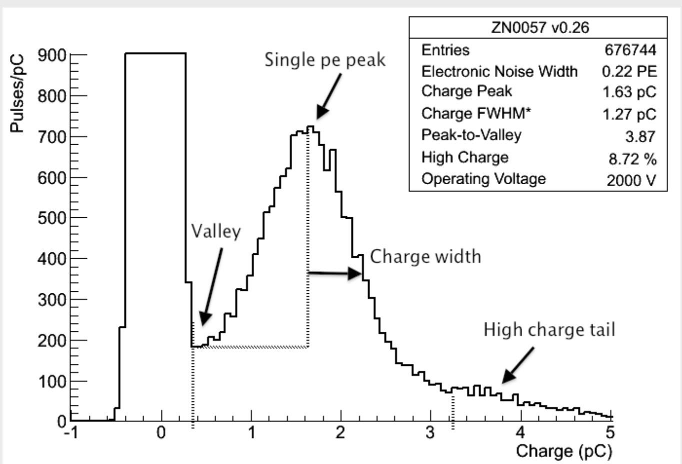
Many tubes discussed in LBNE talks:

- ET9354 ETL 8”
- R7081 Hamamatsu 10”
- XP1804 Photonis 12”
- R11780 Hamamatsu 12”
- R3600 Hamamatsu 20”

Hamamatsu R11780HQE were selected for the reference design

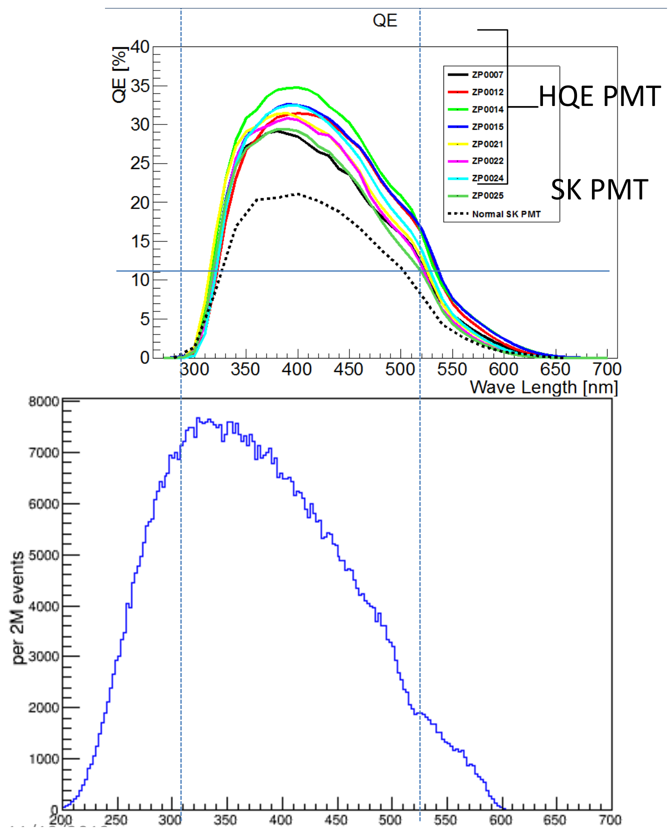
see: http://arxiv.org/abs/1210.2765 http://arxiv.org/abs/1204.2295



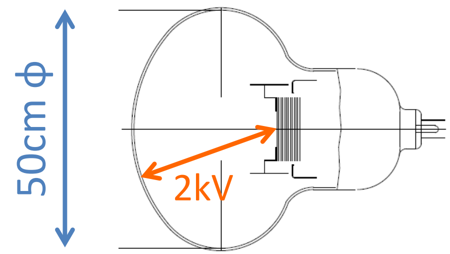


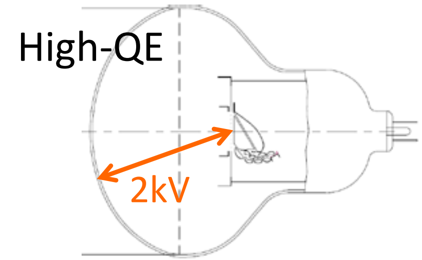
Conventional PMTs

Hyper-K is looking at two primary designs for the gain stage of their conventional phototubes, all available with high-QE photocathodes



credit: F. Retière

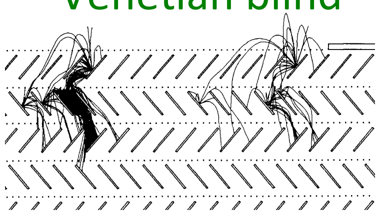




20″ PMT (Venetian-Blind dynode)

- Super-K ID PMTs
- Used for ~20 years
  → Guaranteed
- Complex production
  → Expensive

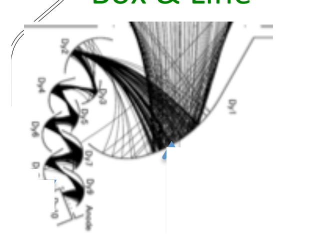
Venetian blind



20″ Improved PMT (Box&Line dynode)

- Under development
- Better performance
- Same technology
  → Lower risk

Box & Line



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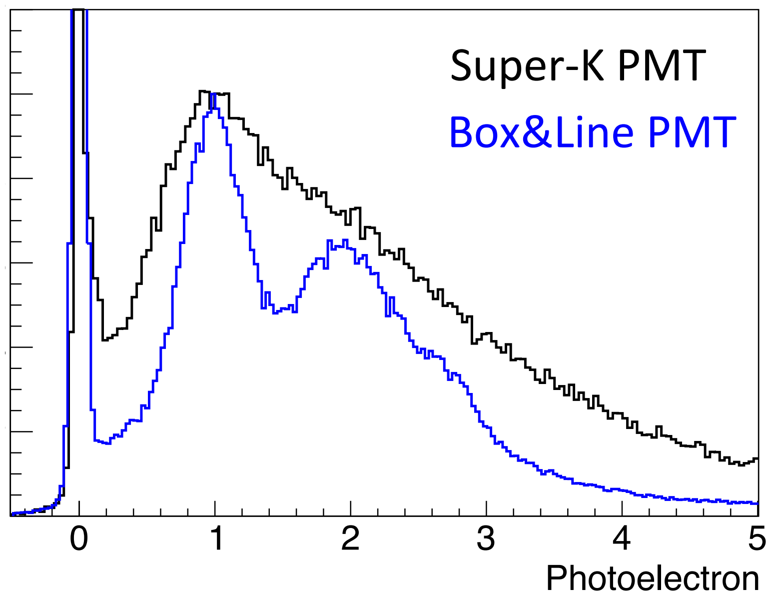
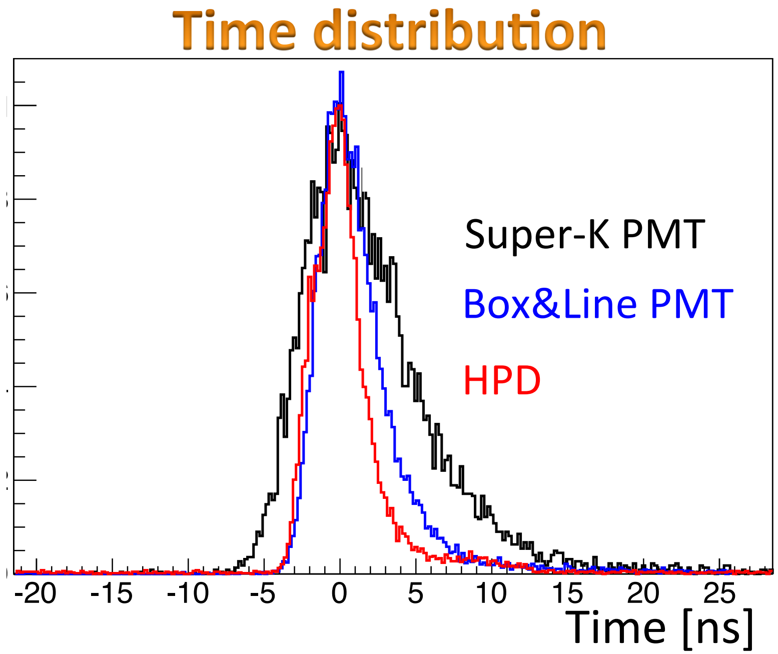
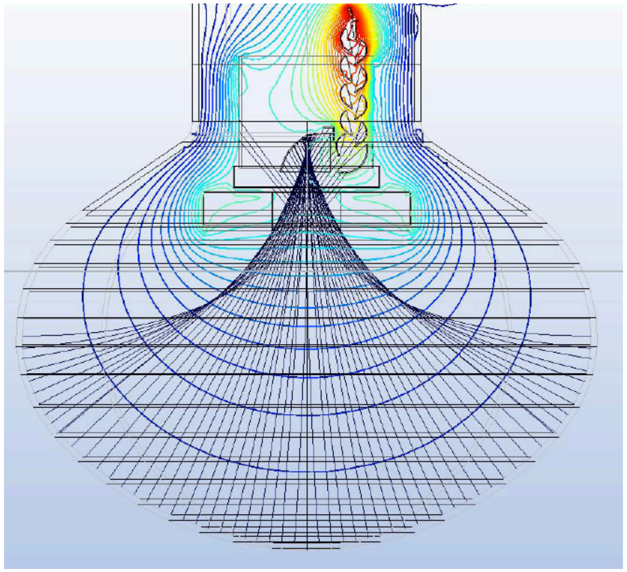




Box&Line PMTs have better collection efficiency, better photon counting, and better time resolution.

credit: Y. Nishimura (from ANT14)

Conventional PMTs



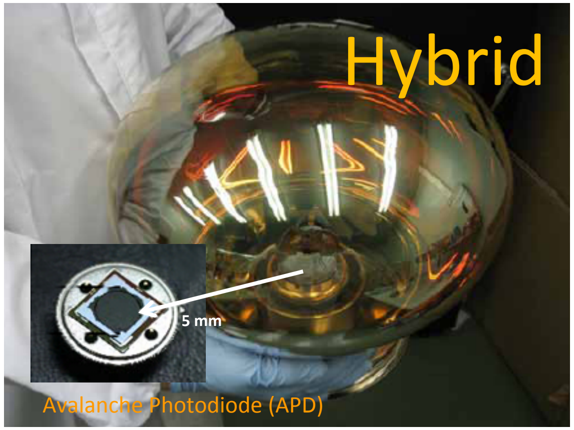
- Develop capabilities of ADIT/ETL companies from Sweetwater Texas
  - Supported by NSF
  - Goal is the development of a US based manufacturer of large area PMTs
- Plan
  - 11" PMTs that could be used for HK veto
  - First prototypes summer 2014
  - Complete tests at Davis, Penn, Drexel by mid 2015

	unit	min	typ	max
photocathode: bialkali				
active diameter	mm		270	
active surface area	cm^2		800	
quantum efficiency at peak	%		30	
luminous sensitivity	µA/lm		70	
with CB filter		8	12	
with CR filter			1	
dynodes: 12LFSbCs				
anode sensitivity in divider A:				
nominal anode sensitivity	A/lm		500	
max. rated anode sensitivity	A/lm		2000	
overall V for nominal A/lm	V		1400	1800
overall V for max. rated A/lm	V		1550	
gain at nominal A/lm	$x 10^6$		7	
dark current at 20 °C:				
dc at nominal A/lm	nA		20	200
dc at max. rated A/lm	nA		80	
dark count rate	s^{-1}		20000	
pulsed linearity (-5% deviation):				
divider A	mA		30	
divider B	mA		100	
pulse height resolution:				
single electron peak to valley	ratio		2	
rate effect (I_a for $\Delta g/g=1\%$):	µA		20	

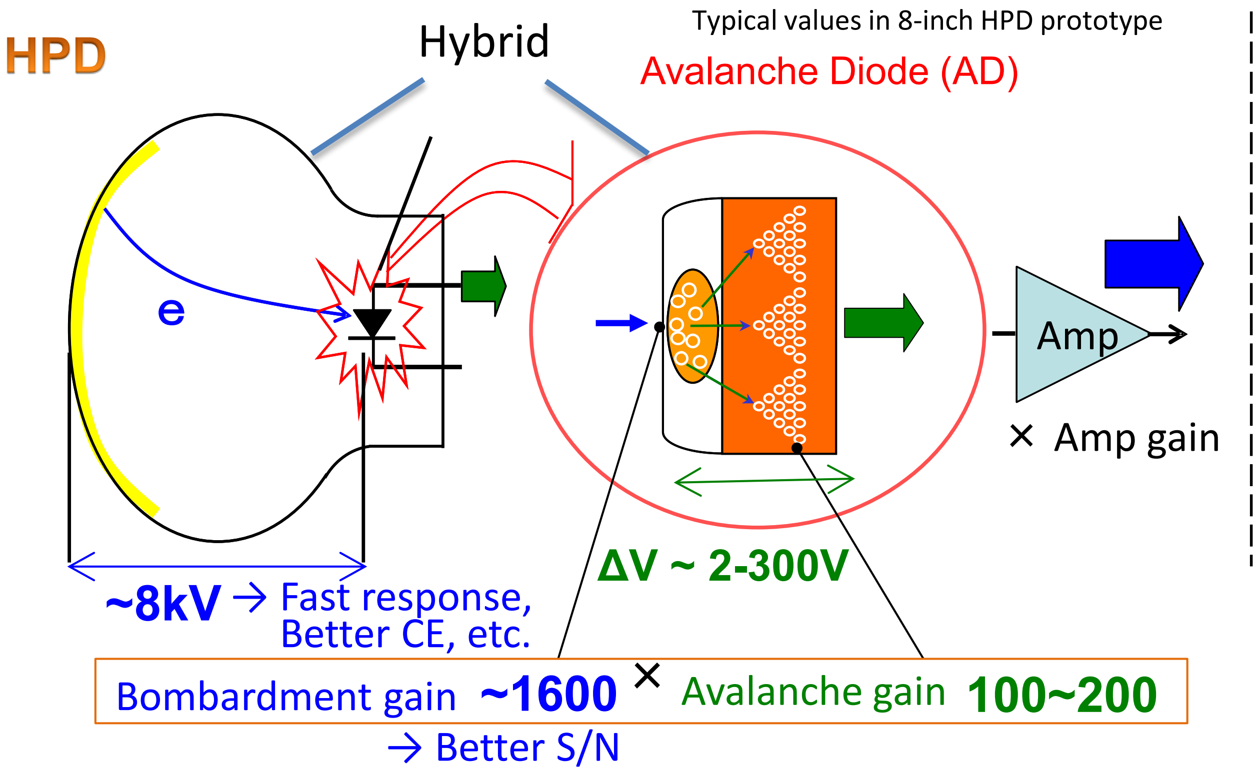
New US option for PMTs. Option being explored by WATCHMAN collaboration.

credit: R. Svoboda

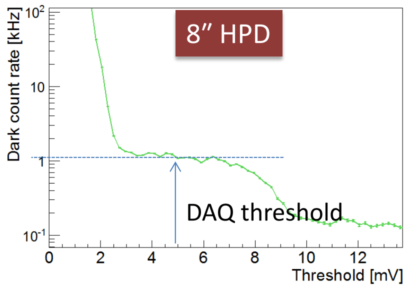
Hybrid Photodetectors

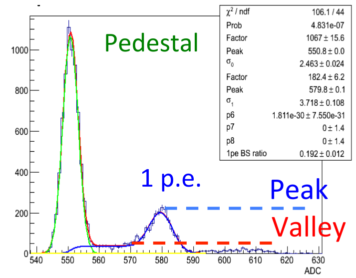


Hyper-K is exploring Hybrid Photodetectors (with solid state gain stages) as an alternative to conventional PMTs

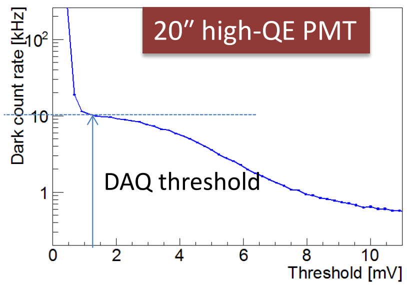


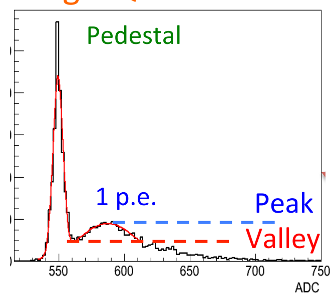
HPDs

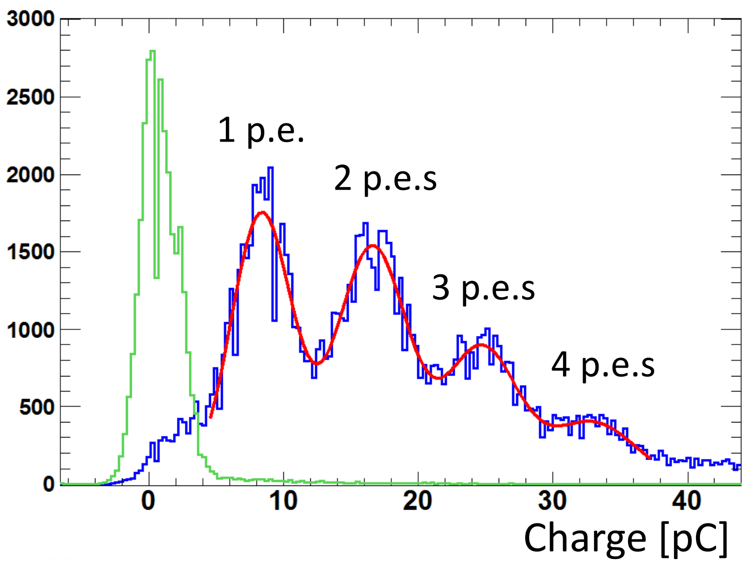




High-QE PMT







	20″ PMT	New 20″ PMT	20″ HPD
Gain	1×10^7	1×10^7	10^4～10^5*
C.E.	80%	93%	95%
T.T.S. (FWHM)	5.5ns	2.7ns	0.75ns*
P/V ratio@1p.e.	1.7	≥2.5	>3

* w/o Preamp

Estimated values

Spectral response		300 - 650 (420 max.) nm
Photocathode		Bialkali
Window material		Borosilicate glass
Gain		4 - 9 x10^4
Time	Rise	1.7 ns
	Fall	2.7 ns
	T.T.S.	0.62 ns (σ)
Dynamic range		100 pC (1.5x10^4 p.e.)

Large Area MCP-PMT development in China

credit: Sen Qian (IHEP)

➢ PMT requirement of JUNO

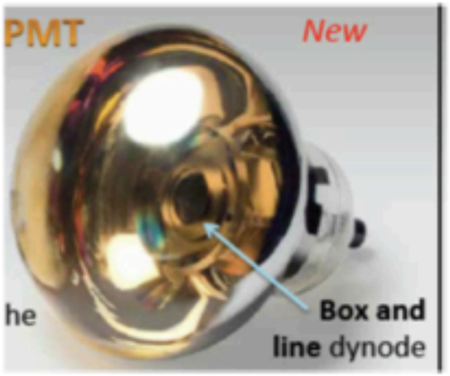
- LS volume: × 20 ➔ for more statistics (40 events/day)
- Light (PE) × 5 ➔ for better resolution ($\Delta M^2_{12} / \Delta M^2_{23} \sim 3\%$)

◆ **Three types of high QE 20" PMTs under development:**

- ⇨ Hammamatsu PMT with SBA photocathode
- ⇨ A new design using MCP: 4π collection
- ⇨ Photonics-type PMT

Requirement:

- ✓ High QE 20 inch PMT;
- ✓ Good SPE detection capability;
- ✓ Wide dynamic range;
- ✓ Low radioactive background;
- ✓ More than 20 years lifetime;
- ✓ Can withstand 0.4MPa Pressure;
- ✓ > 15000 pieces;

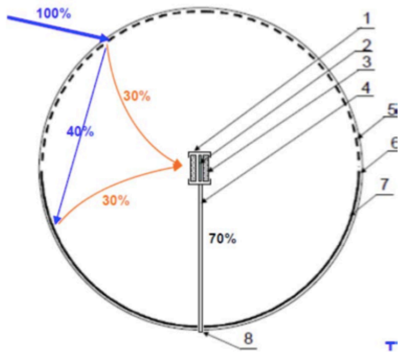


➢20" Hammamatzu PMT

➢20" MCP- PMT

Large Area MCP-PMT development in China

credit: Sen Qian (IHEP)



The Design MCP-PMT

The Prototype

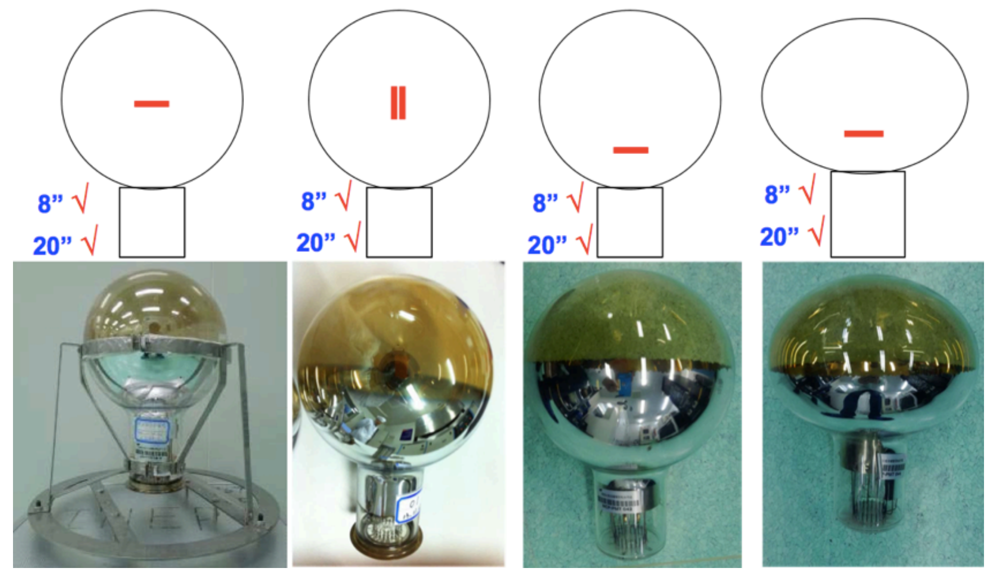
- Small (33mm) MCPs as a compact gain stage.
- Novel combination of transmissive and reflective photocathodes, geometry and electron optics to increase QE.

$PD = QE_{Trans}{*}CE + TR_{Photo}QE_{Ref}{*}CE = 30\%{*}70\% + 40\%{*}30\%{*}70\% = 30\%$

Photon Detection Efficiency: 15% → 30% ; ×~2 at least !

Testing prototypes with a variety of geometries and electron optics.

Sphere ball One MCP module	Sphere ball Two MCP modules	Sphere ball One MCP module	Ellipsoidal ball One MCP module



Large Area MCP-PMT development in China

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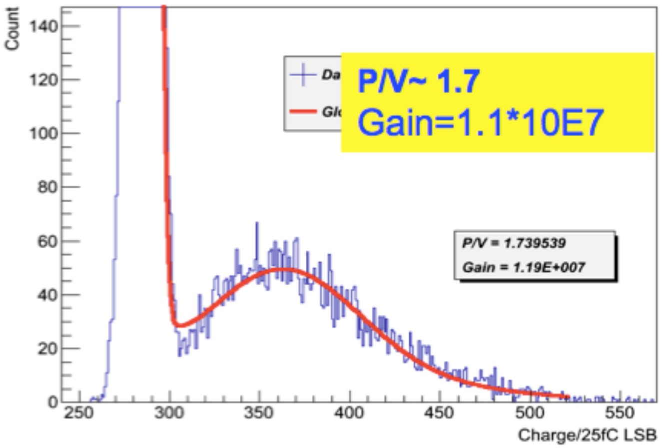
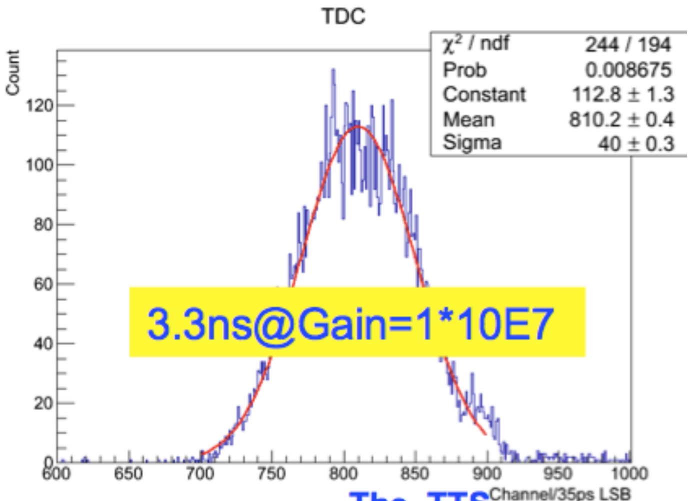
First 20” prototype

The Prototype



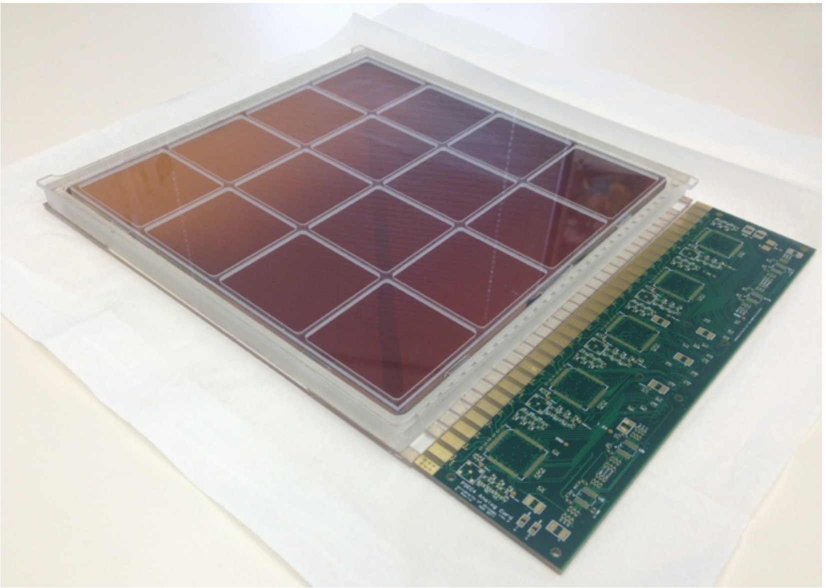
The SPE of the PMT



The TTS

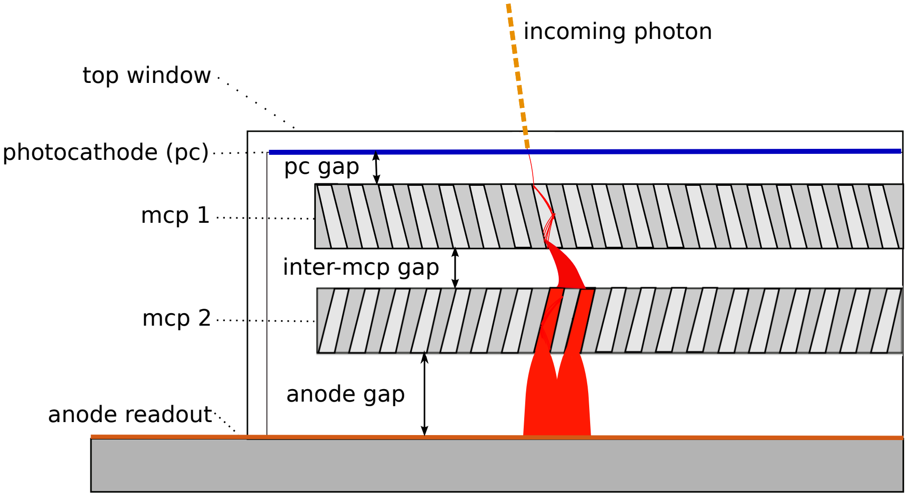
Now working on improvements to quantum efficiency and collection efficiency

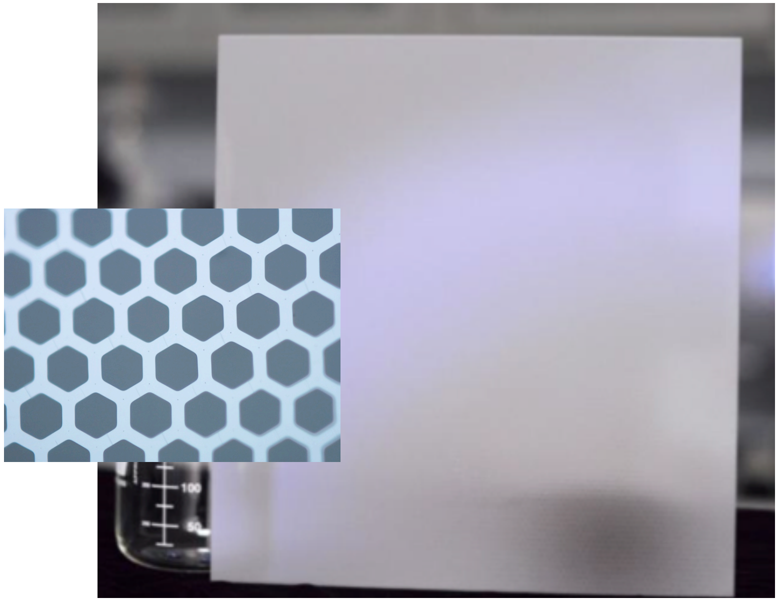
LAPPD project



The Large Area Picosecond Photodetectors (LAPPD):

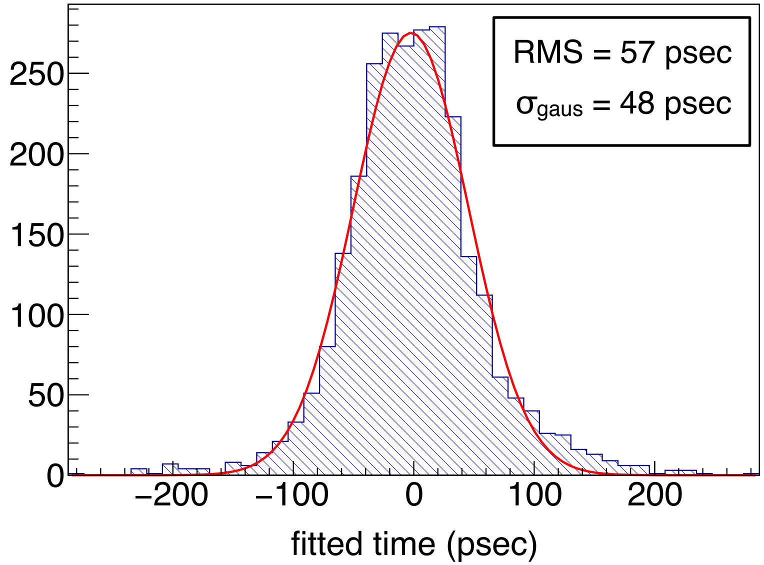
- large, flat-panel, MCP-based photosensors
- 50-100 psec time resolutions and <1cm spatial resolutions
- based on new, potentially economical industrial processes.
- LAPPD design includes a working readout system.



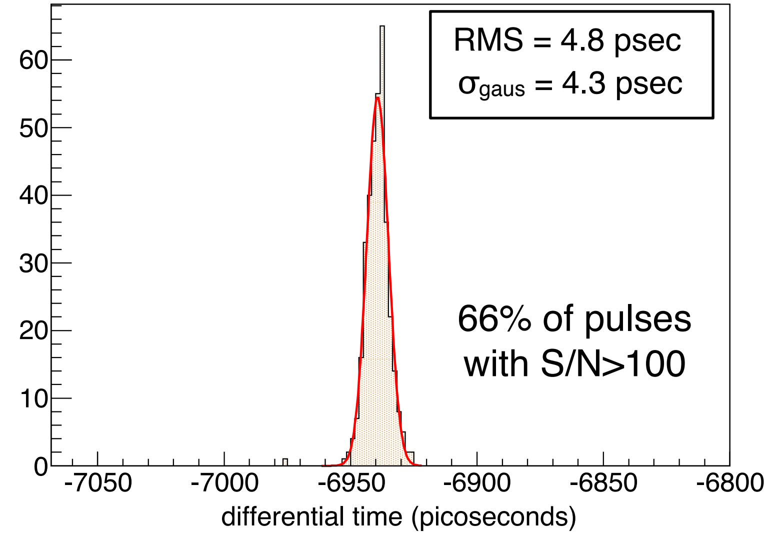


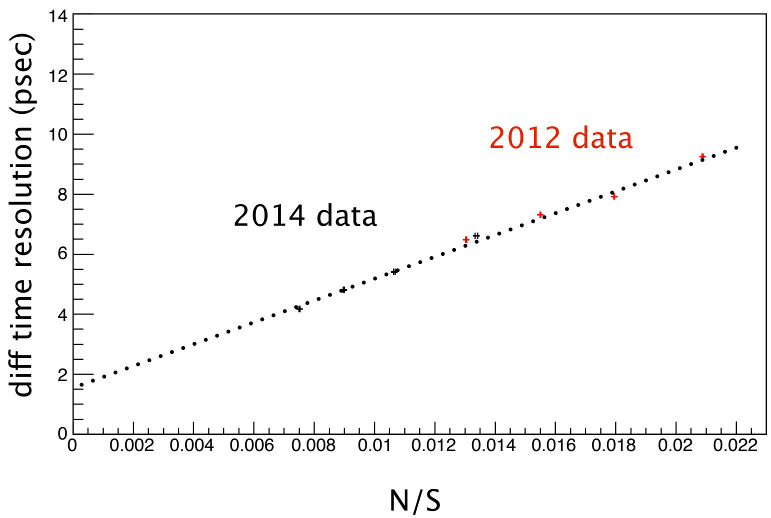
LAPPD capabilities

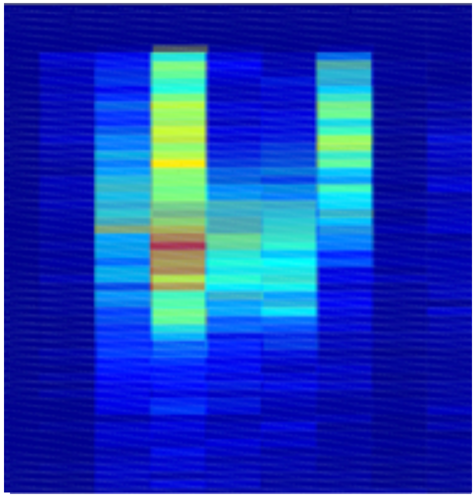
single photoelectron absolute time resolution



differential time resolution between 2 ends of stripline







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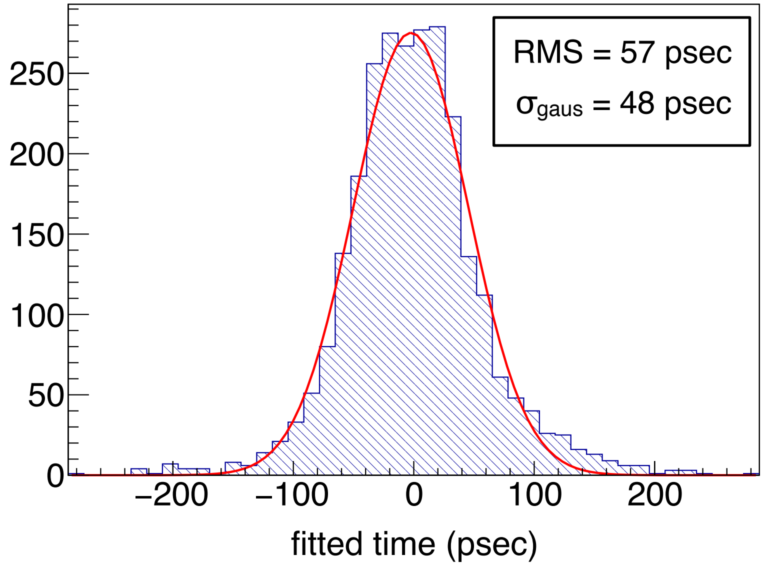

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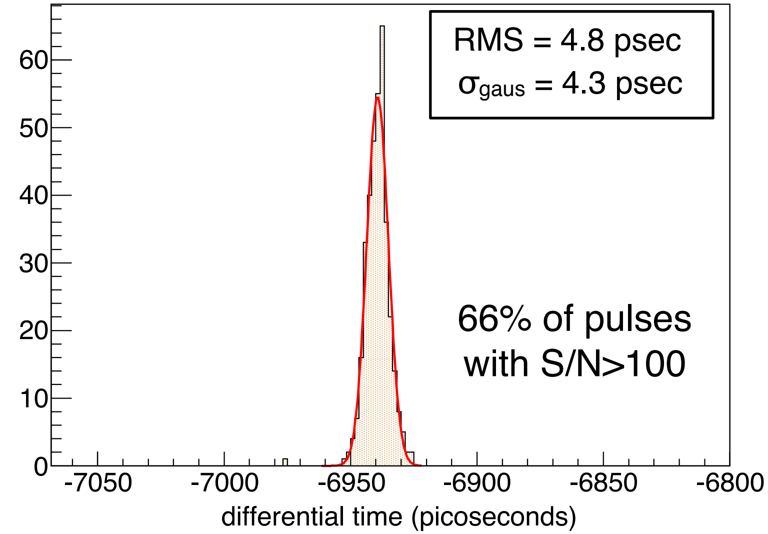
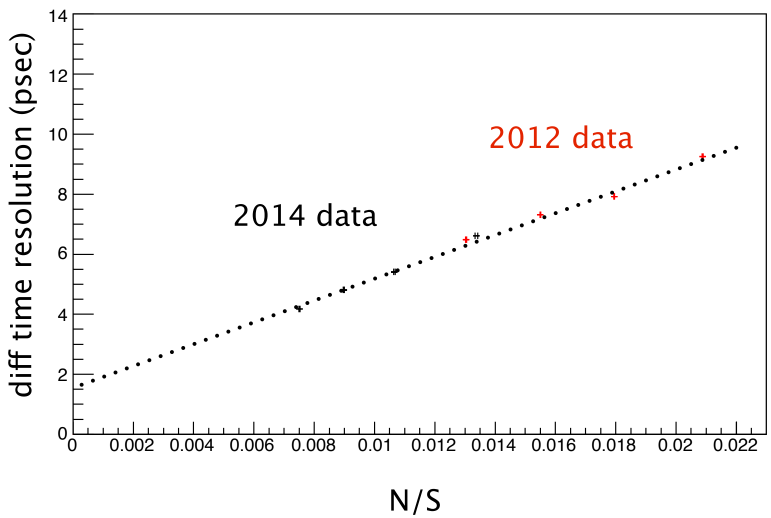
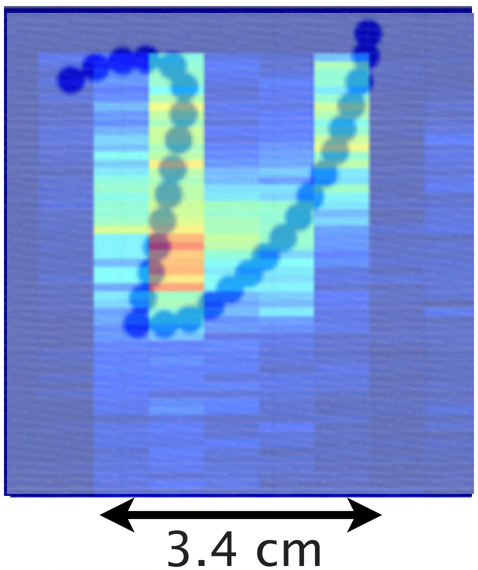
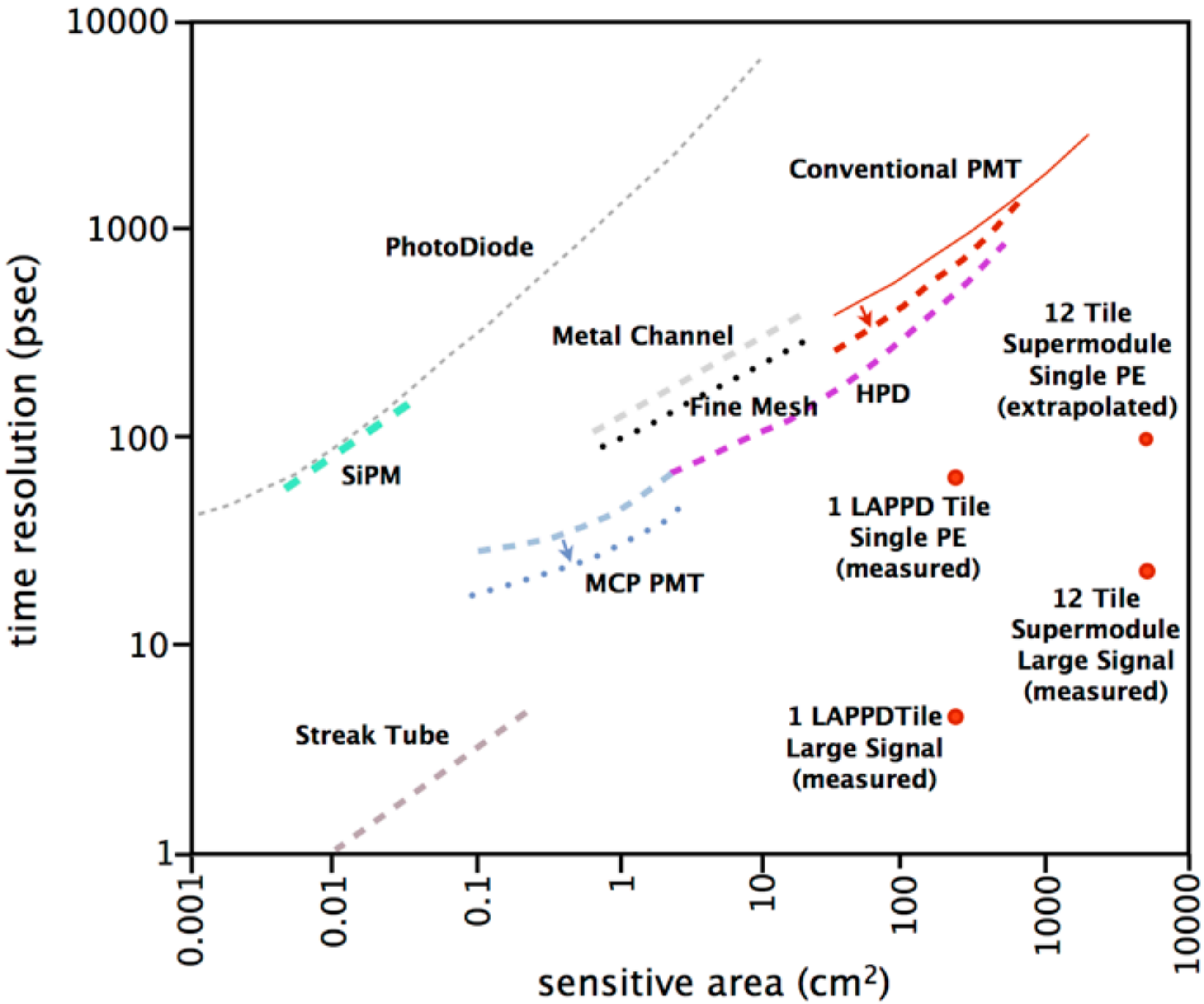






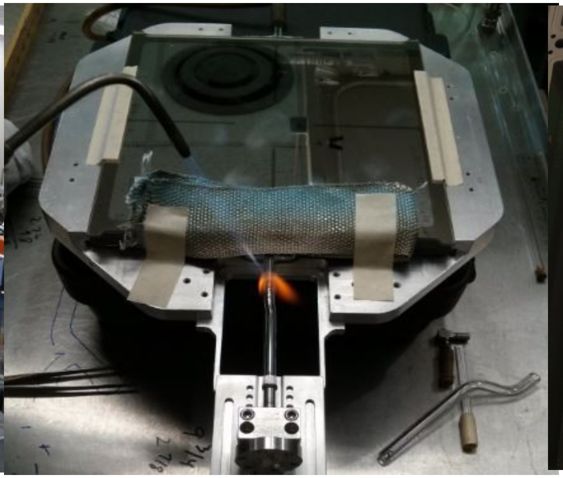
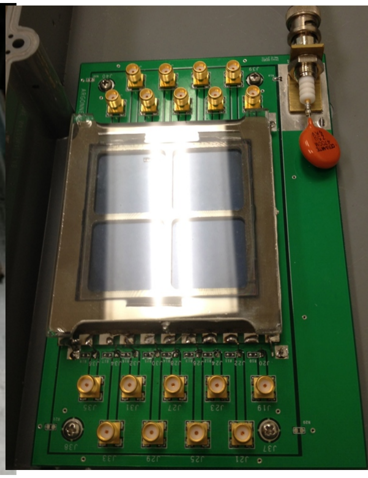
LAPPD capabilities



LAPPD status

- $3 M in STTR funding has been provided to Incom for commercialization of LAPPDs.
- Berkeley SSL: just funded to make a small number of tiles this year
- Argonne has successfully sealed small-format glass tiles (6 cm x 6 cm) using similar process and design
- U Chicago is commissioning an advanced fabrication facility, developing ways to lower cost and improve yields



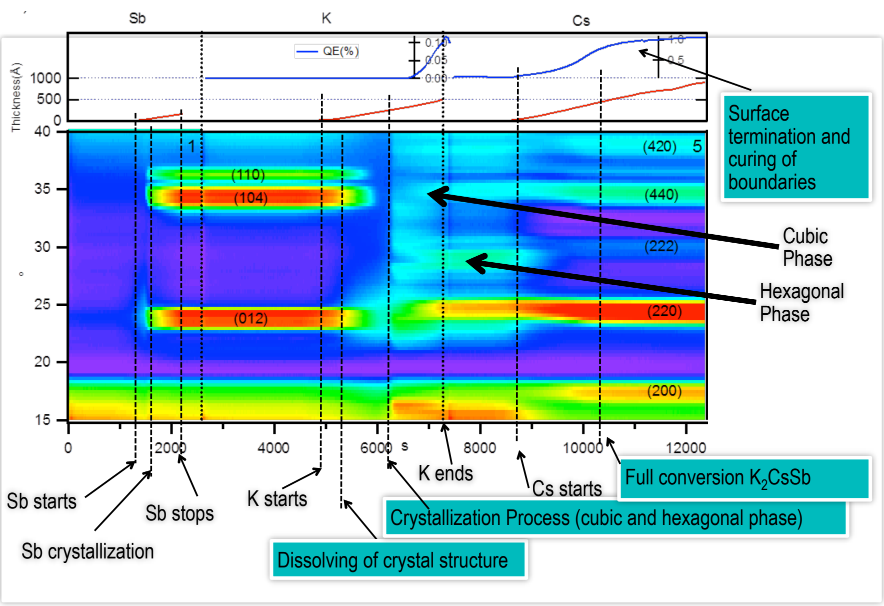



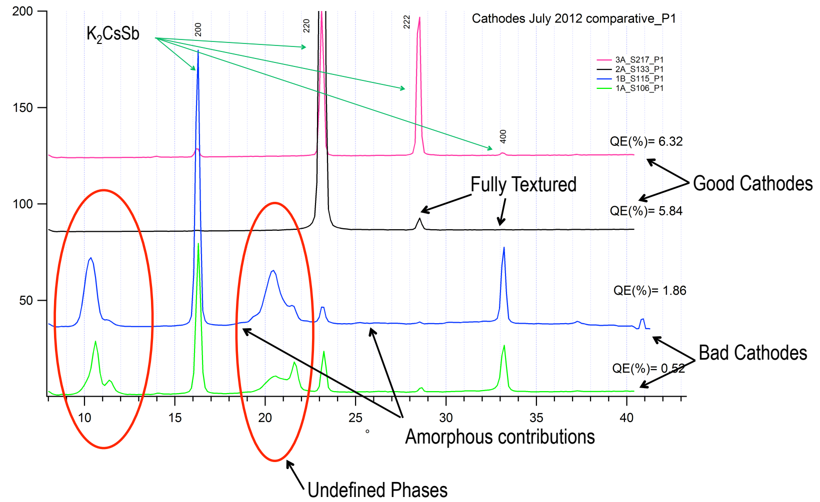
Generic Photocathode Research

Photocathode work: John Smedley (BNL), Howard Padmore (LBNL), RMD, Henry Frisch (University of Chicago), Klaus Attenkofer (BNL)

Understanding of growth recipes

- Characterization tools are established which allows to visualize crystal growth and roughness during processing.
- Sb-metal melting process demonstrated.
- Rough cathode structure is most likely determined by stoichiometry conditions during processing.
- Understanding of p- n-dopants of cathode structures due to alkali deficiencies and surface termination.

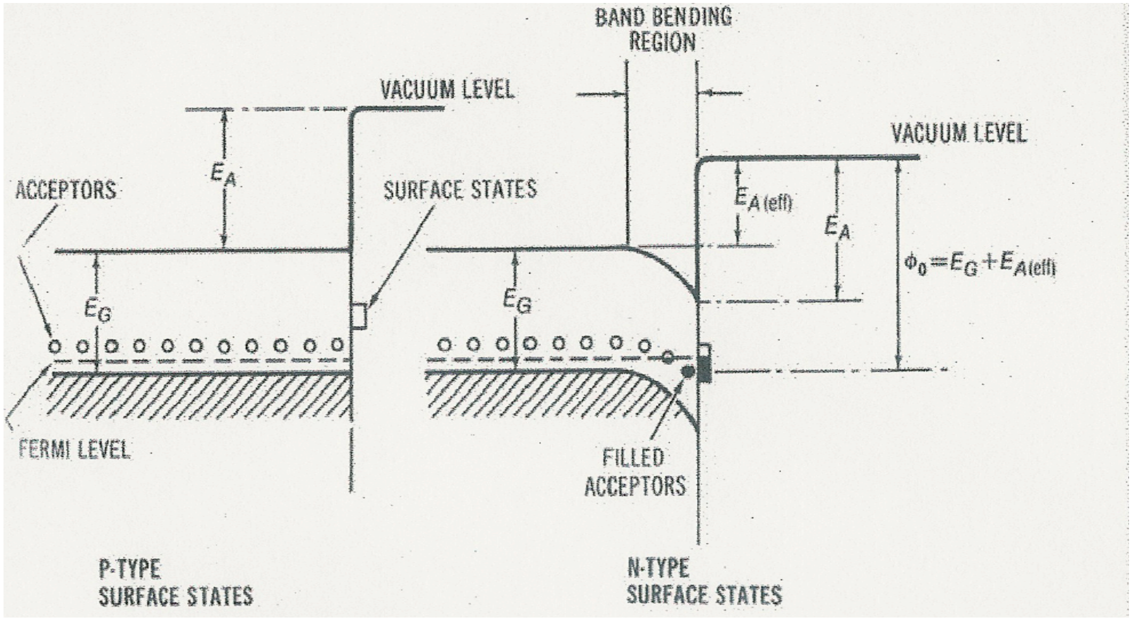




Towards sputtering:

- Macroscopic amount of material can be produced (also allowing bulk measurements like mobility….)
- Target fabrication is successful
- Substitution dopant are under evaluation
- All hardware is currently designed and installed

credit: Klaus Attenkofer (BNL)

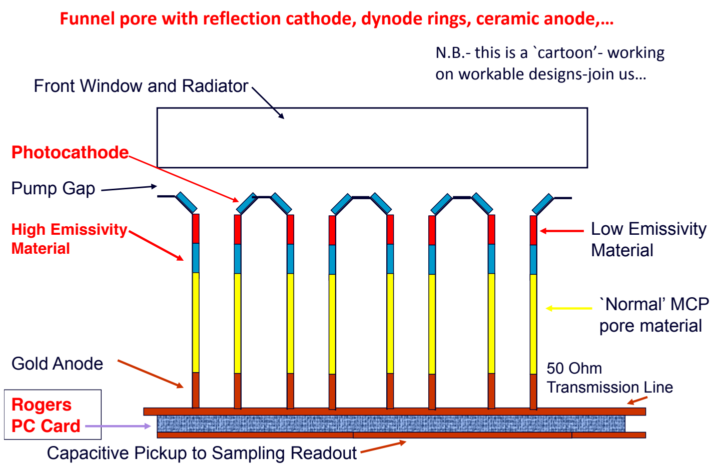


A Photocathode is a simplified "pn-junction":

1. Alkali deficiency in the "bulk" provides p-doping of the cathode (indication by XPS data)

2. Excess Cs on the surface creates a N-doped surface resulting in band bending and reduced work function (explains 0.7eV electron affinity)

Other interesting gain structures

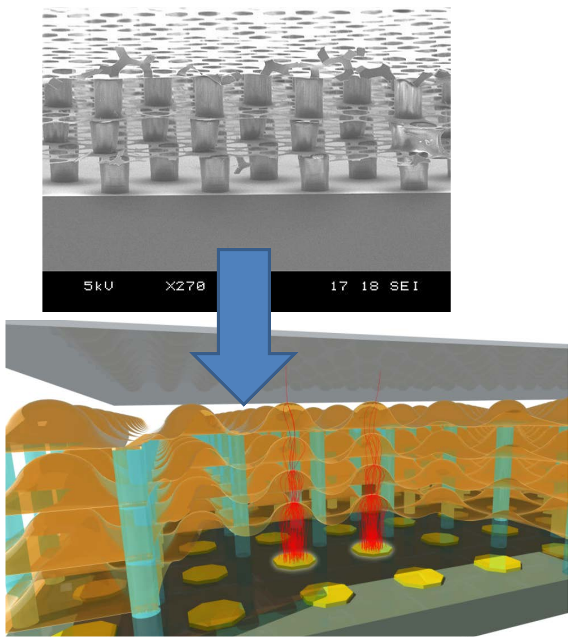


Advanced channel plate concepts:

Funnel geometry with cathode on top surface.

Structured coatings

credit: H Frisch (UC)



Tipsy principle

use pixel chip as 2D sensitive anode
dynode stack above individual pixel
set of closely spaced *transmission* dynodes

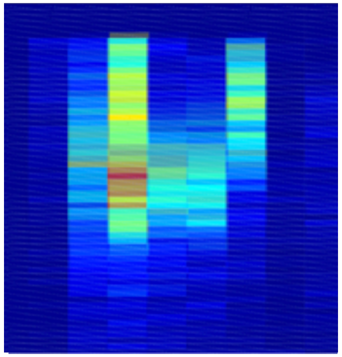
Similar to gaseous detector and micromegas

MEMs technology to fabricate layers of thin membranes

Harry Vandergraf, et al. See MCP workshop at ANL: https://indico.hep.anl.gov/indico/conferenceDisplay.py?confId=411

Spatial granularity/ Digital Photon Counting

$$\mathcal{L}(\mathbf{x}) = \prod_{\text{unhit}} (1 - P(i\ \text{hit}; \mathbf{x})) \times \prod_{\text{hit}} P(i\ \text{hit}; \mathbf{x})\ f_q(q_i; \mathbf{x})\ f_t(t_i; \mathbf{x})$$



with conventional PMTs

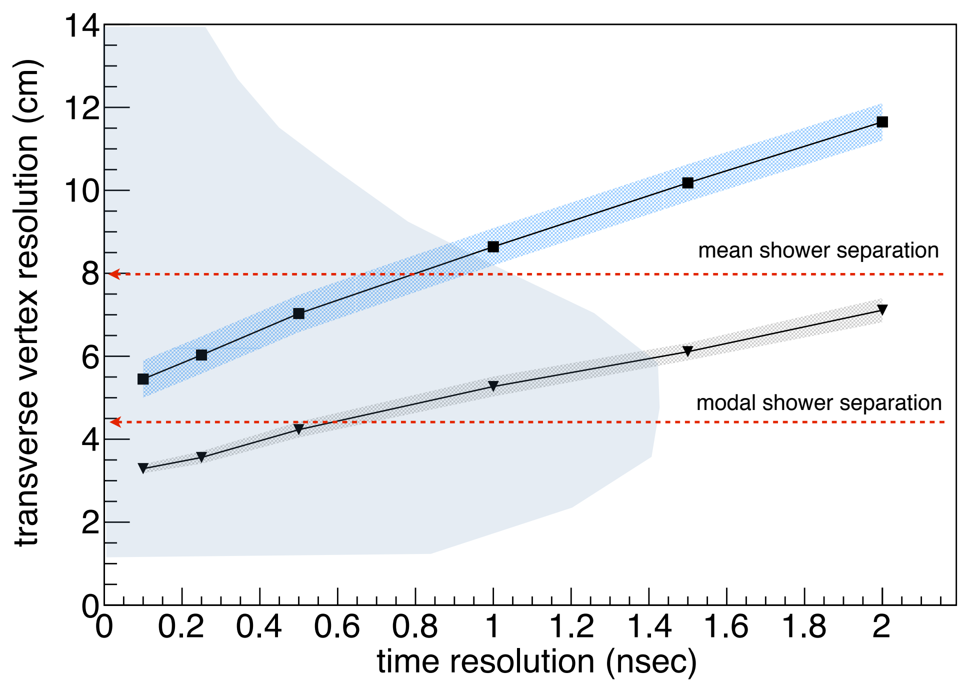
- Measure a single time-of-first-light and a multi-PE blob of charge
- Likelihood is factorized into separate time and charge fits
- History of the individual photons is washed out

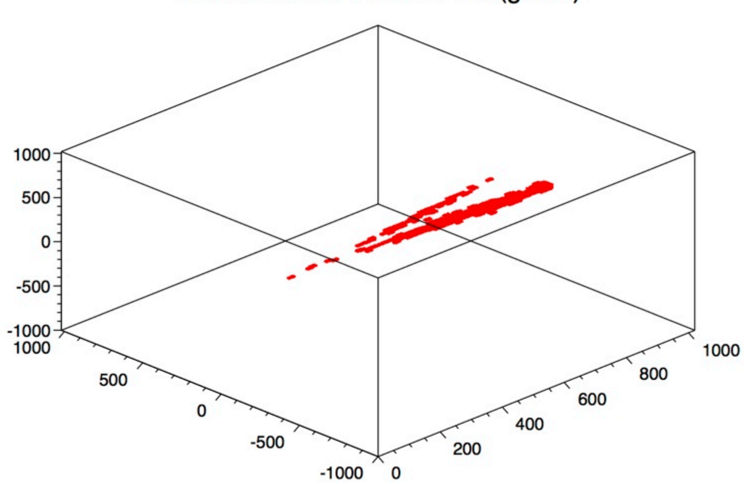
with hires imaging tubes

- Measure a 4-vector for each individual photon
- Likelihood based on simultaneous fit of space and time light
- one can separately test each photon for it's track of origin, color, production mechanism (Cherenkov vs scintillation) and propagation history (scattered vs direct)

Precision Timing

Timing can be used to reduce π^0 backgrounds on high-E beams

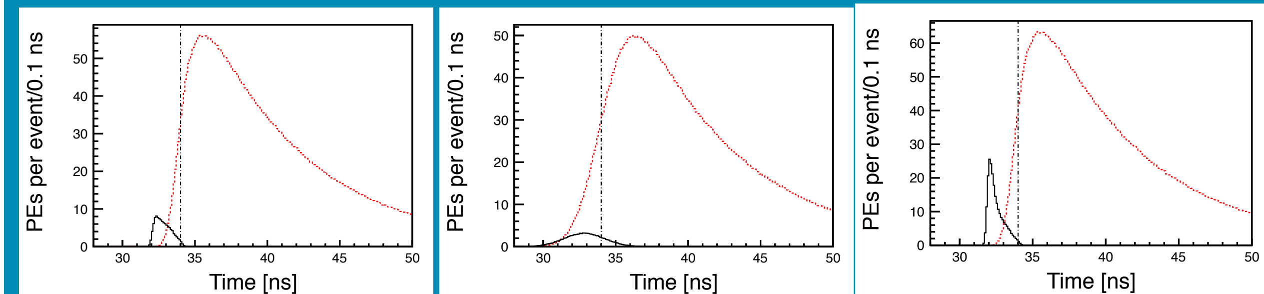




Time reversal algorithms ("working backwards") provide narrow down the details of the event.

Cherenkov – Scintillation Hybrids

Timing to separate between Cherenkov and scintillation light



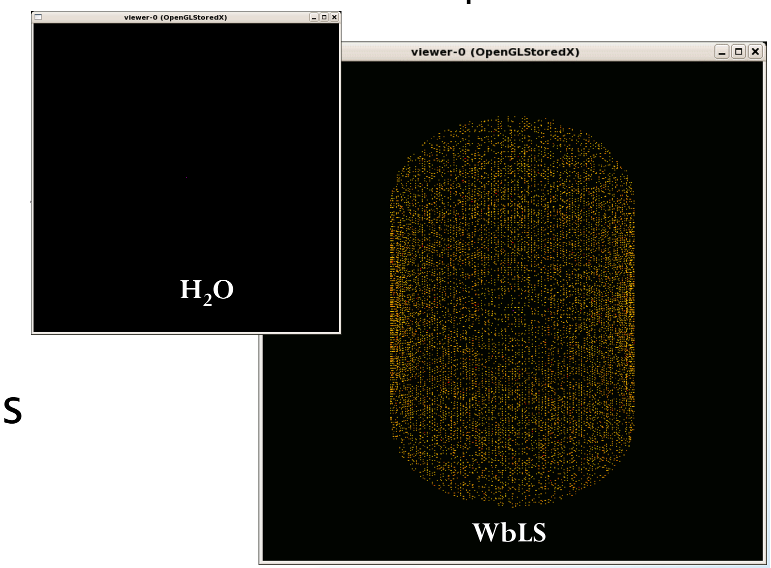
(a) Default simulation. (b) Increased TTS (1.28 ns). (c) Red-sensitive photocathode.

C. Aberle, A. Elagin, H.J. Frisch, M. Wetstein, L. Winslow. Measuring *Directionality in Double-Beta Decay and Neutrino Interactions with Kiloton-Scale Scintillation Detectors;*

arXiv:1307.5813

Cherenkov + scintillation -> tracking + calorimetry

K+ in water and liquid scintillator



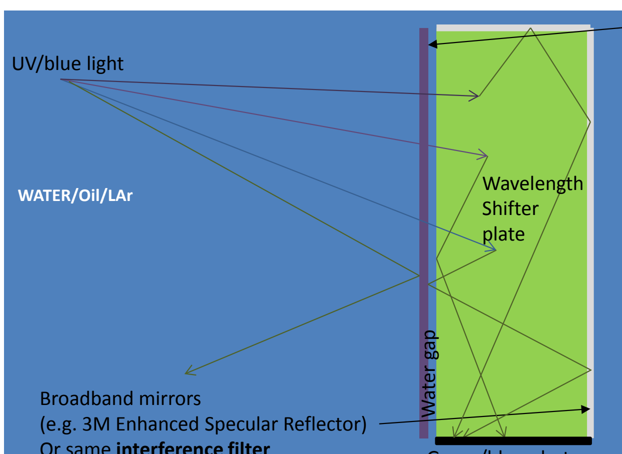
M. Yeh, et al (BNL)

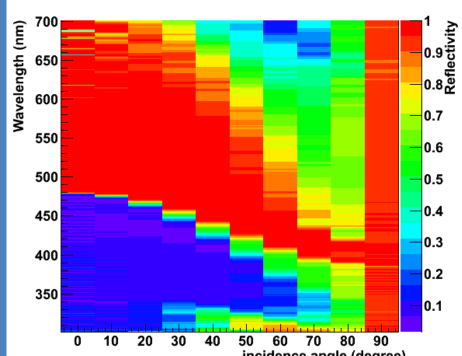
Detecting scintillation light as a means of seeing particles below Cherenkov threshold

Light Collection

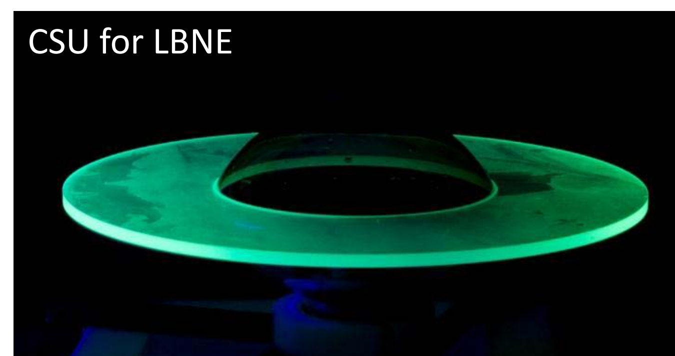
Light collectors can be used to improve collection area per PMT

- Winston cones:
  - significant improvement in coverage
  - isochronos
  - but reduces fiducial volume
- Wavelength shifters
  - improves coverage
  - but reduces time resolution reemits light
- Optical traps
  - uses total internal reflection to trap light





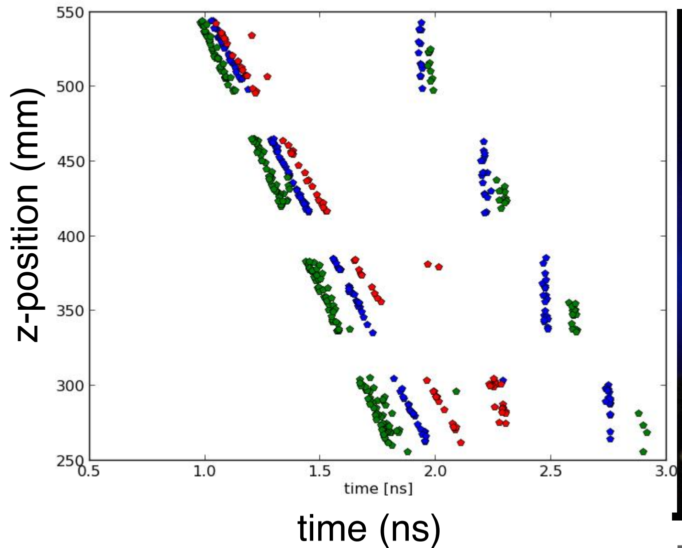
Dichroic mirror by Iridian. Inc
Ottawa, Canada

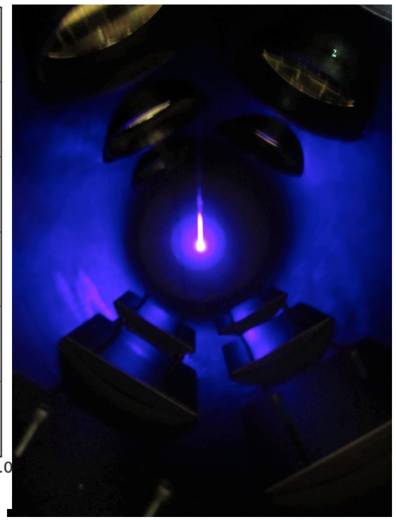


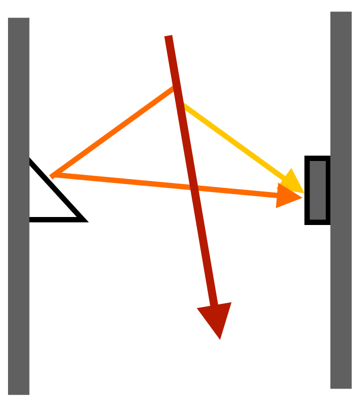
credit: F. Retière

Imaging

It may be possible to increase light collection through imaging optics, mapping the light onto a smaller surface.







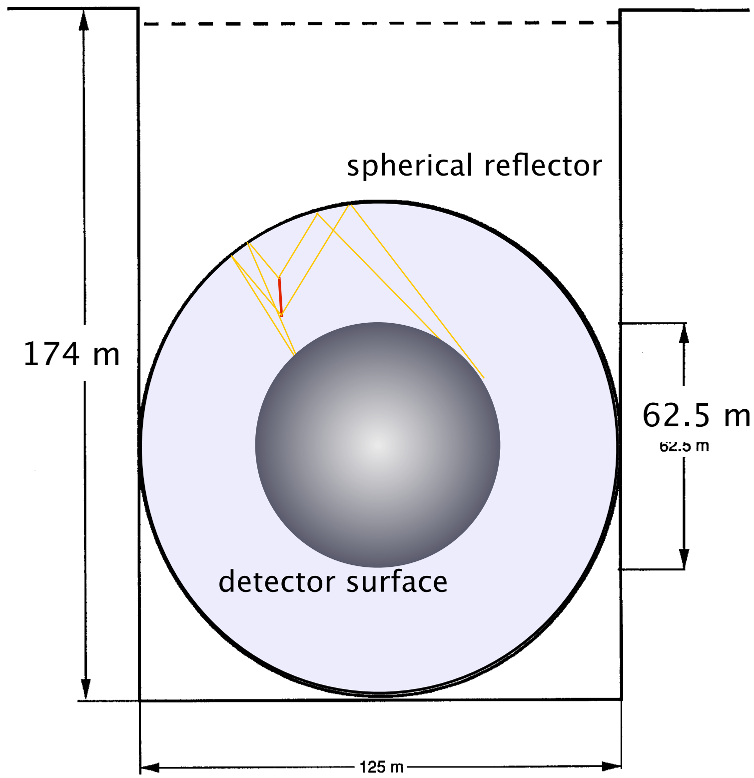
“Optical TPC”

E. Oberla, H. Frisch, R. Northrop

A long, tubular geometry with mirrors reflecting Cherenkov light back at MCPs.

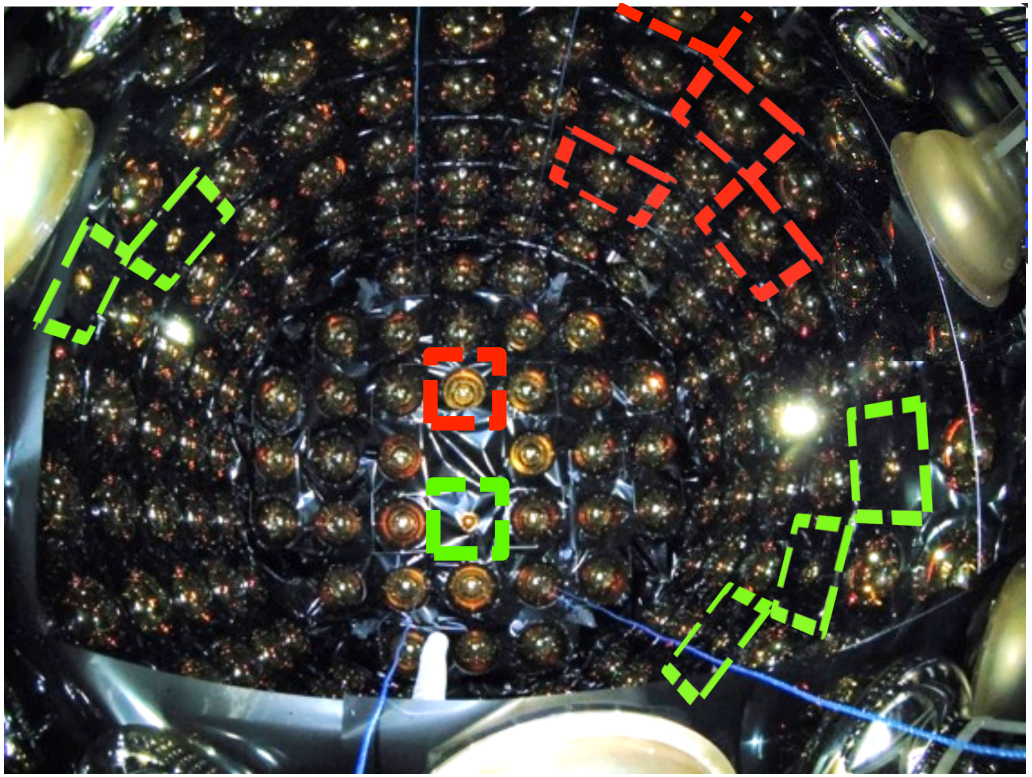
Aqua-RICH

Nuclear Instruments and Methods in Physics Research A 433 (1999) 104}120

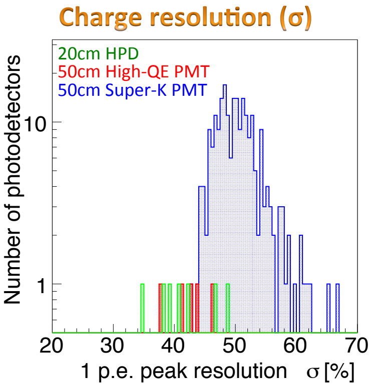


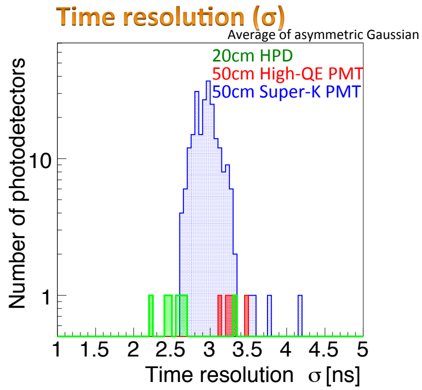
Evaluating Gadolinium's Action in Detectors

200 ton detector (240 PMTs) for studying technical issues involved in Gd-loaded water detectors.

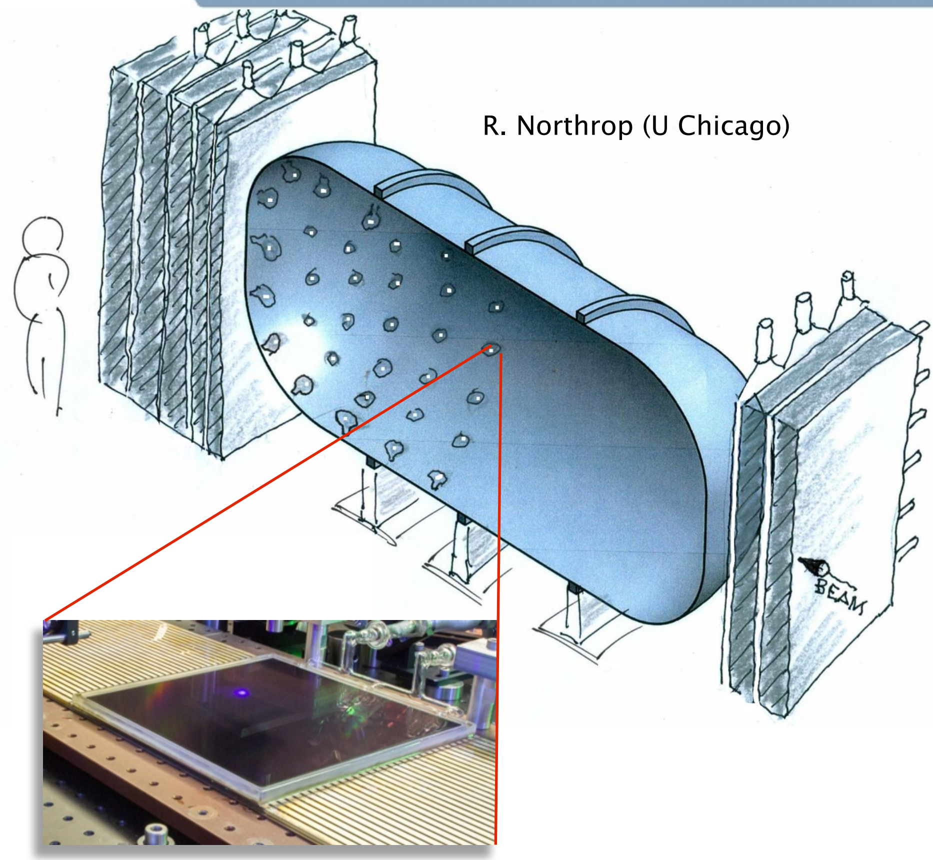


Also, a test bed for studying the performance of conventional PMTs and HPDs under development for Hyper-K





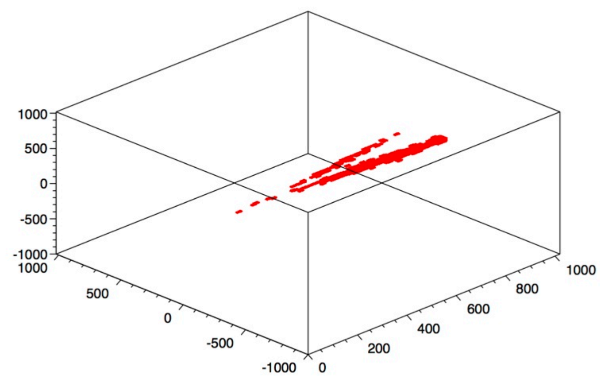
ANNIE
Accelerator Neutrino Neutron Interaction Experiment



A high impact physics measurement:

- the abundance of final state neutrons from neutrino interactions in water
    - can help constrain neutrino-nucleus interaction models
    - an effective handle for signal/bkgd separation in a variety of physics analyses: PDK, wrong-sign identification, SN nuetrinos, etc

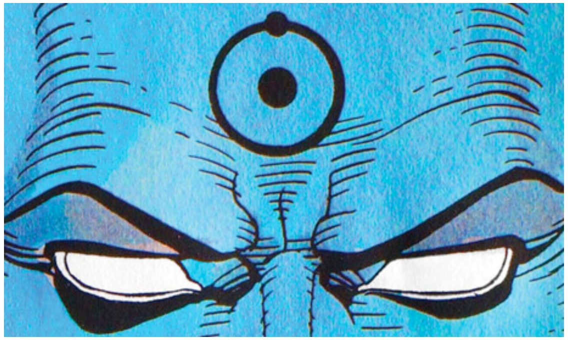
Reconstructed 1.5 GeV Pi0 (geant)



An important detector R&D project:

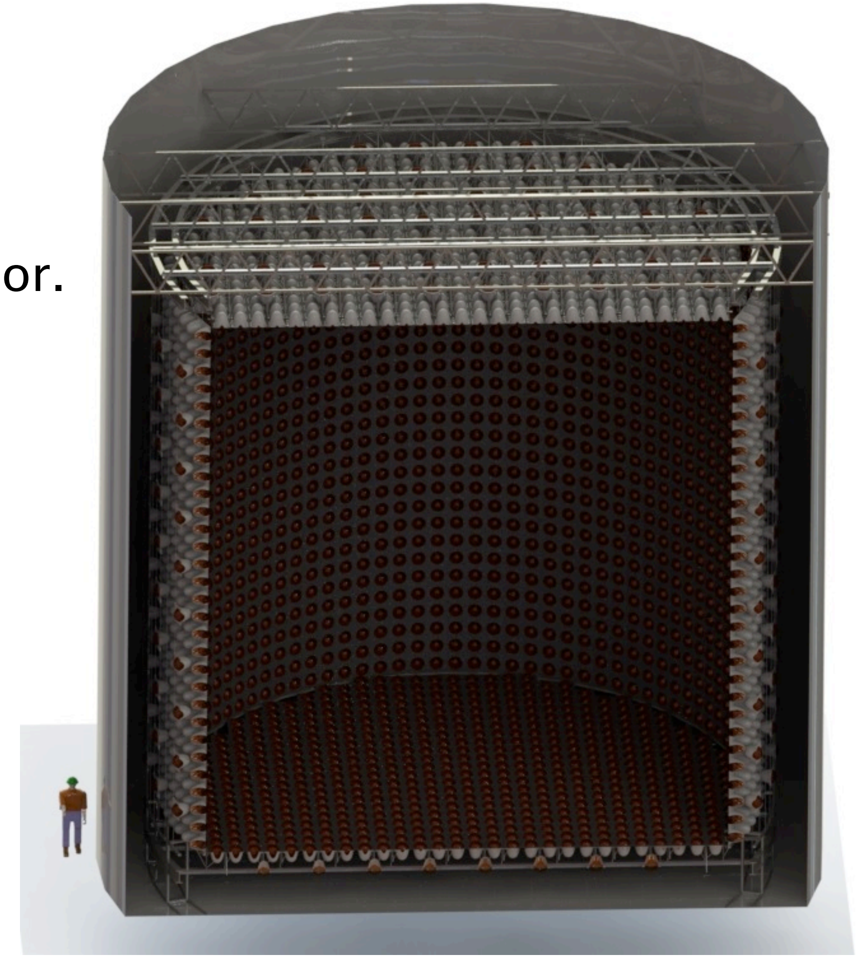
- first application of Large Area Picosecond Photodetectors (LAPPDs) in water-based neutrino detectors.

WATCHMAN -WATer CHerenkov Monitor of Anti-Neutrinos



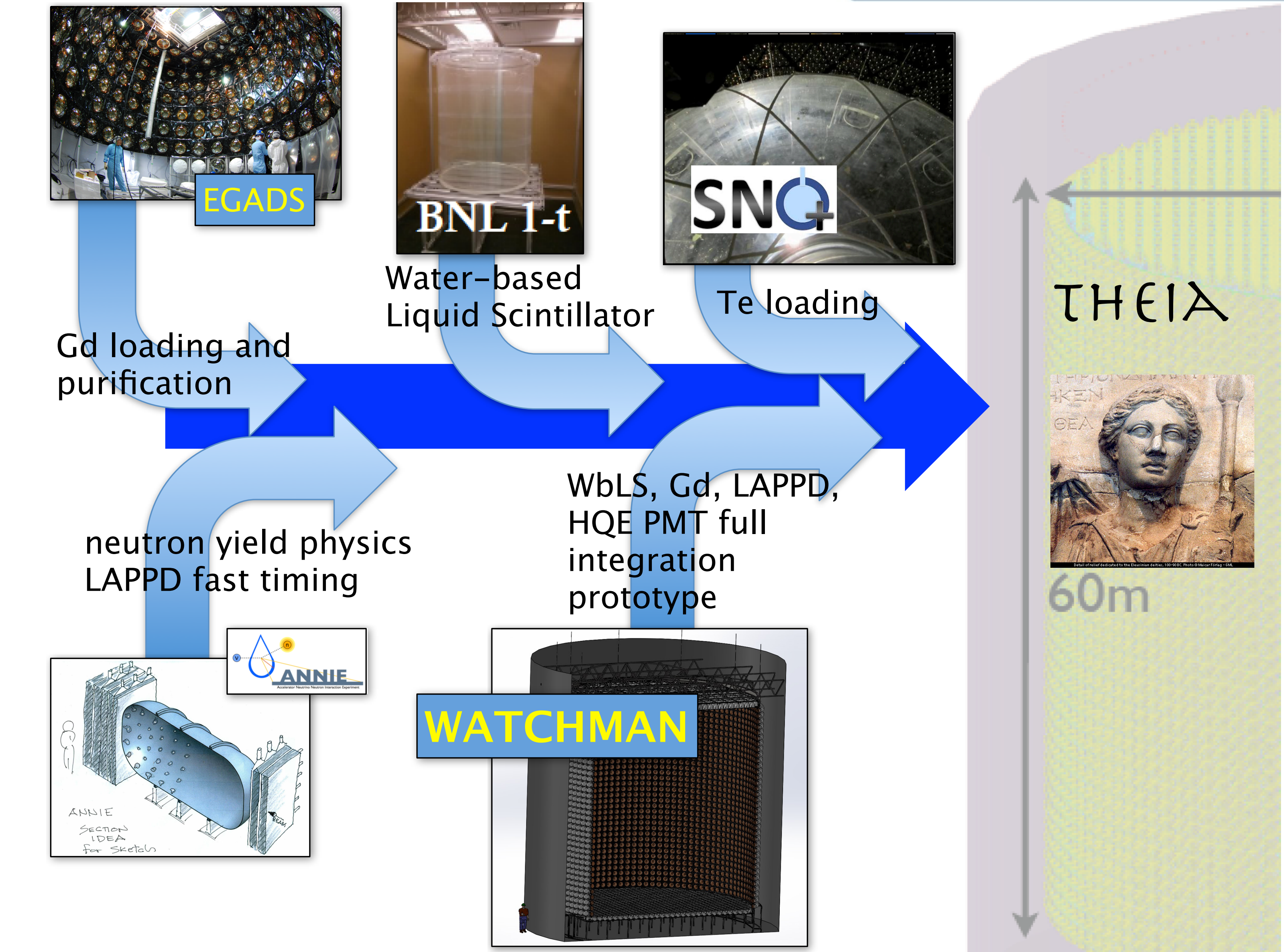
A demonstration of remote, neutrino-based reactor monitoring using a Gd-loaded WCh.

Will be the largest US SN neutrino detector.



Possible oscillation physics program in combination with IsoDar (cyclotron neutrino source).

An opportunity to test LAPPDs in a large scale detector, and with water-based liquid scintillator.

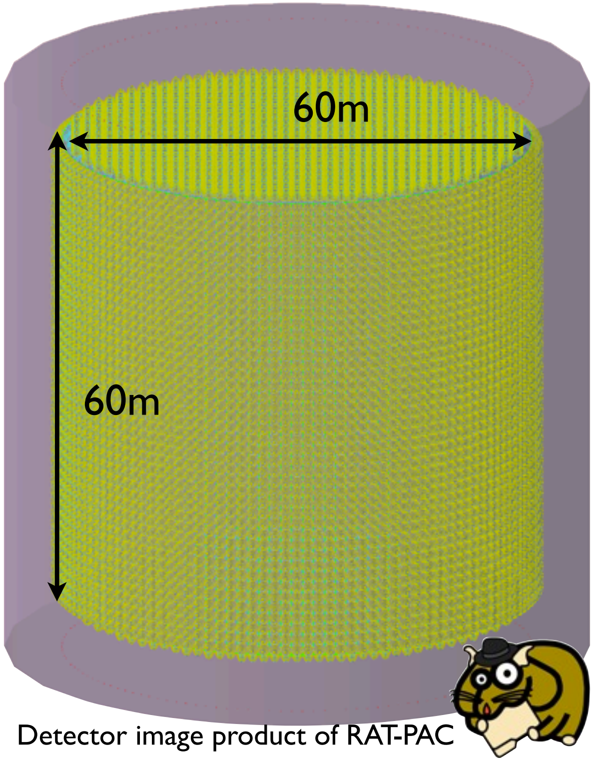

EGADS
BNL 1-t
SNO+
Water-based
Liquid Scintillator
Te loading
Gd loading and
purification
THEIA
60m
neutron yield physics
LAPPD fast timing
WbLS, Gd, LAPPD,
HQE PMT full
integration
prototype
ANNIE
WATCHMAN

The "BIG" Picture

Over the next 5-10 years, it may be possible to develop new and advanced water and scintillator neutrino detectors concepts

These detectors can bring a much needed scale and physics diversity to neutrino experiments in the US and abroad.

THEIA



Detector image product of RAT-PAC

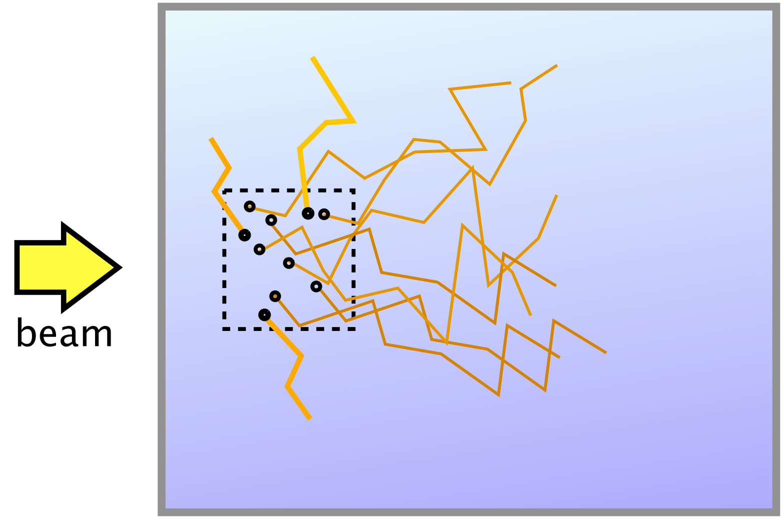
A key ingredient in advancing this technology is the development of advanced photosensors.

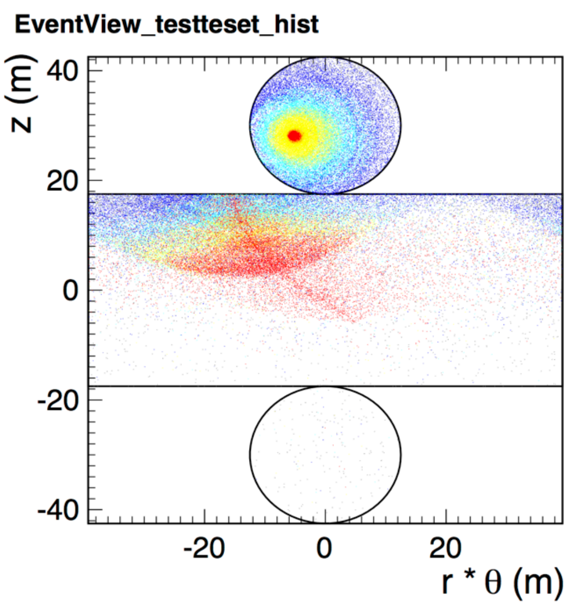
Modest investments in R&D and in small and medium scale experiments can go a long way in making this new technology happen.

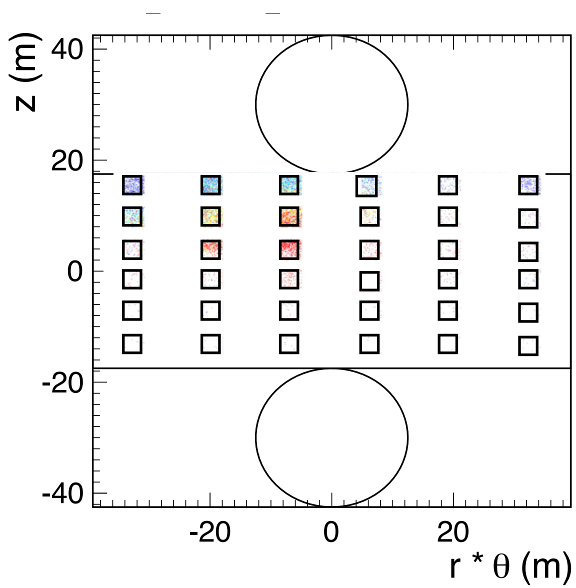
Thank You

LAPPDs can provide the needed photodetector capabilities

Timing based reconstruction to choose interaction points sufficiently far from the walls of the detector to stop the neutrons



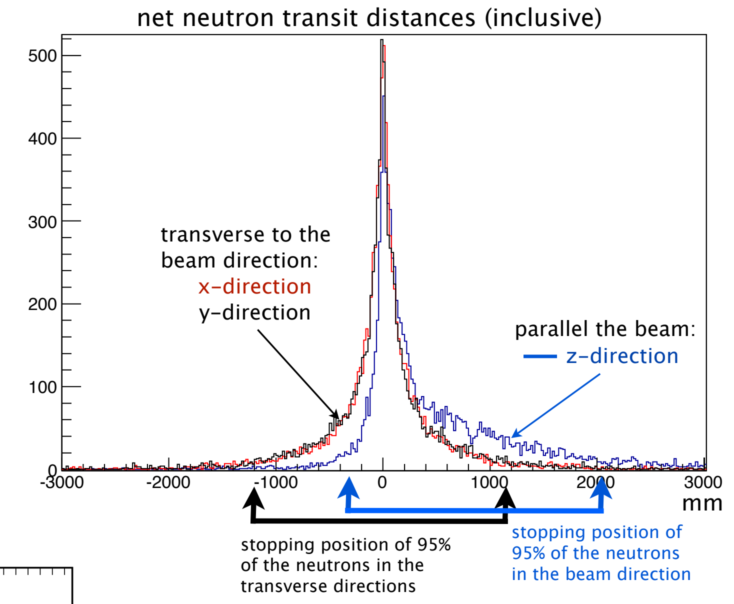


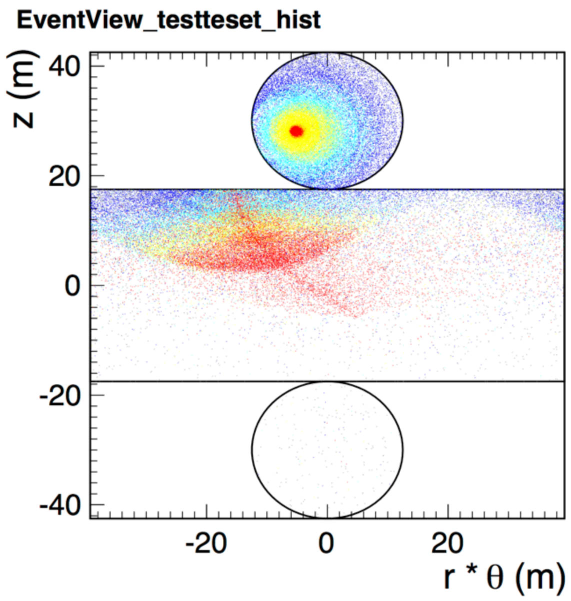


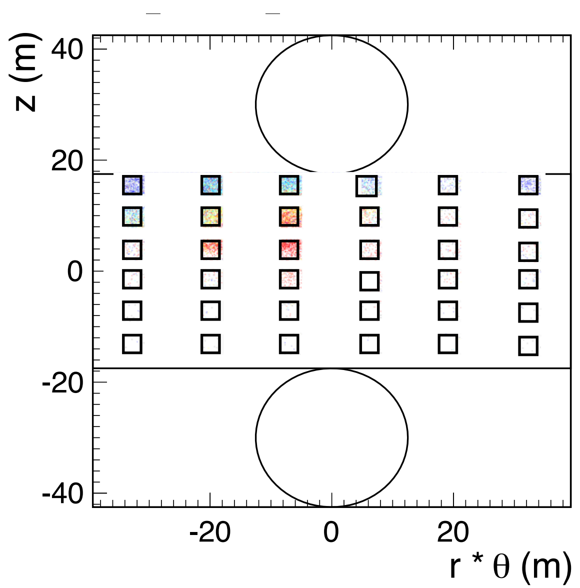
Fine granularity to help resolve Cherenkov cone-edges

LAPPDs can provide the needed photodetector capabilities

Timing based reconstruction to choose interaction points sufficiently far from the walls of the detector to stop the neutrons

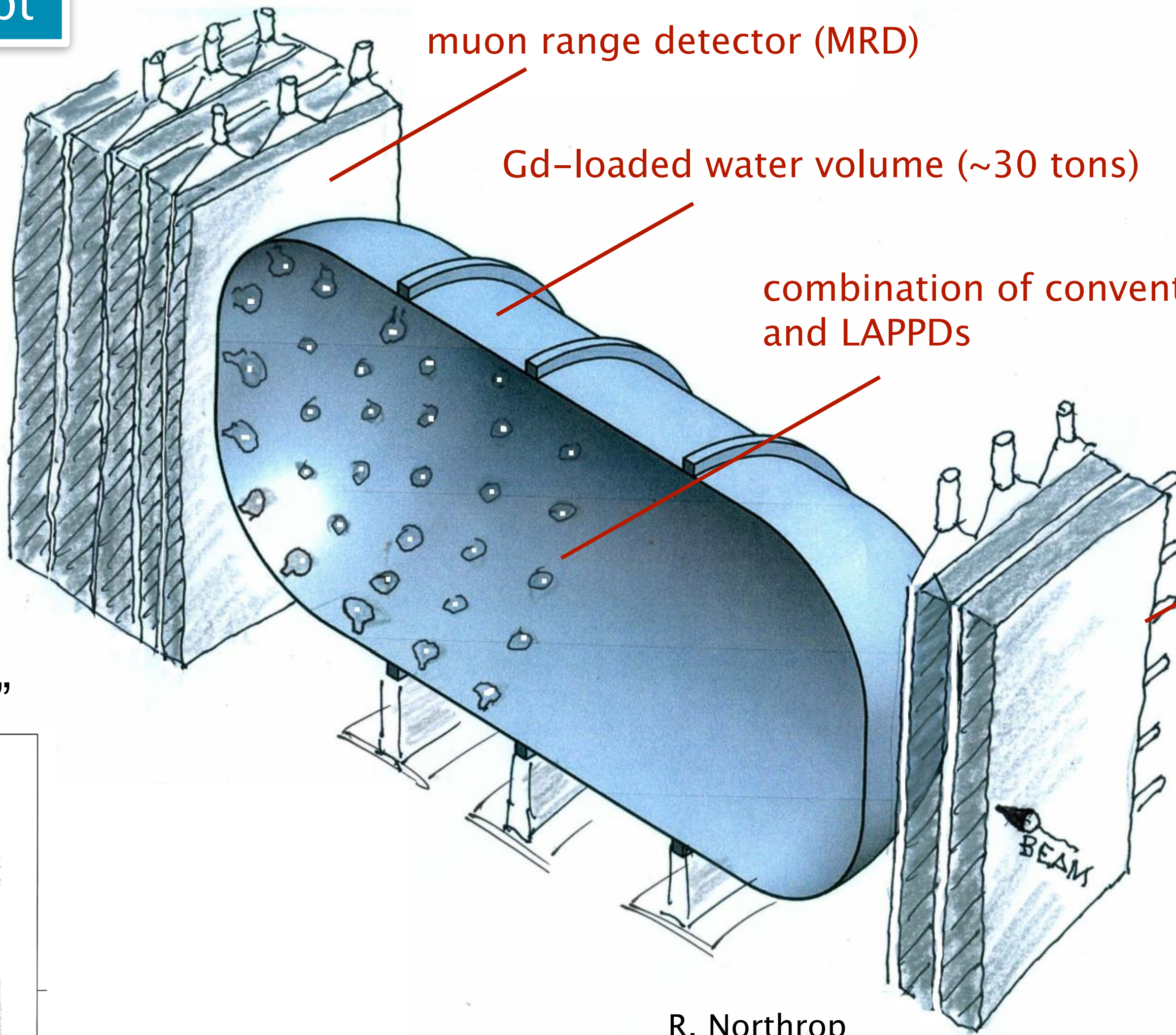




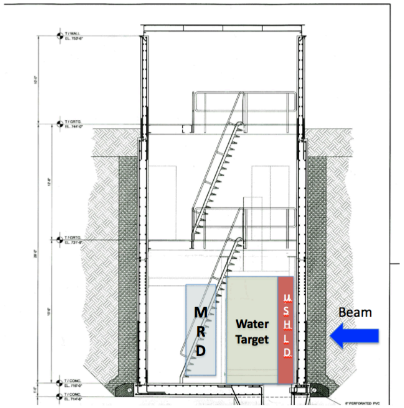


Fine granularity to help resolve Cherenkov cone-edges

ANNIE Concept

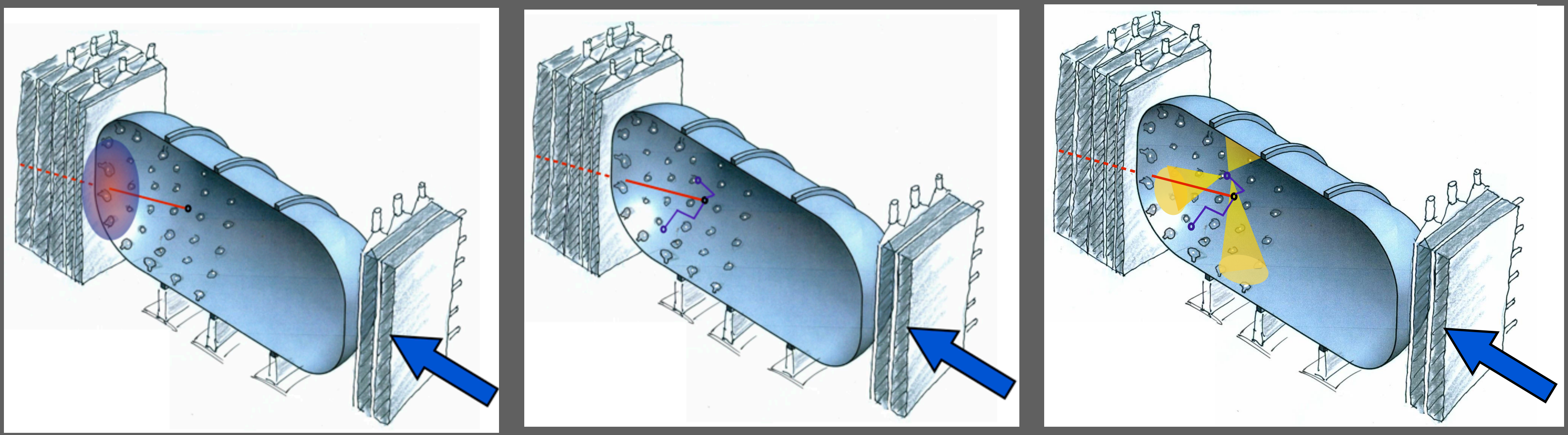


“ANNIE Hall”



(formerly the SciBooNE pit)

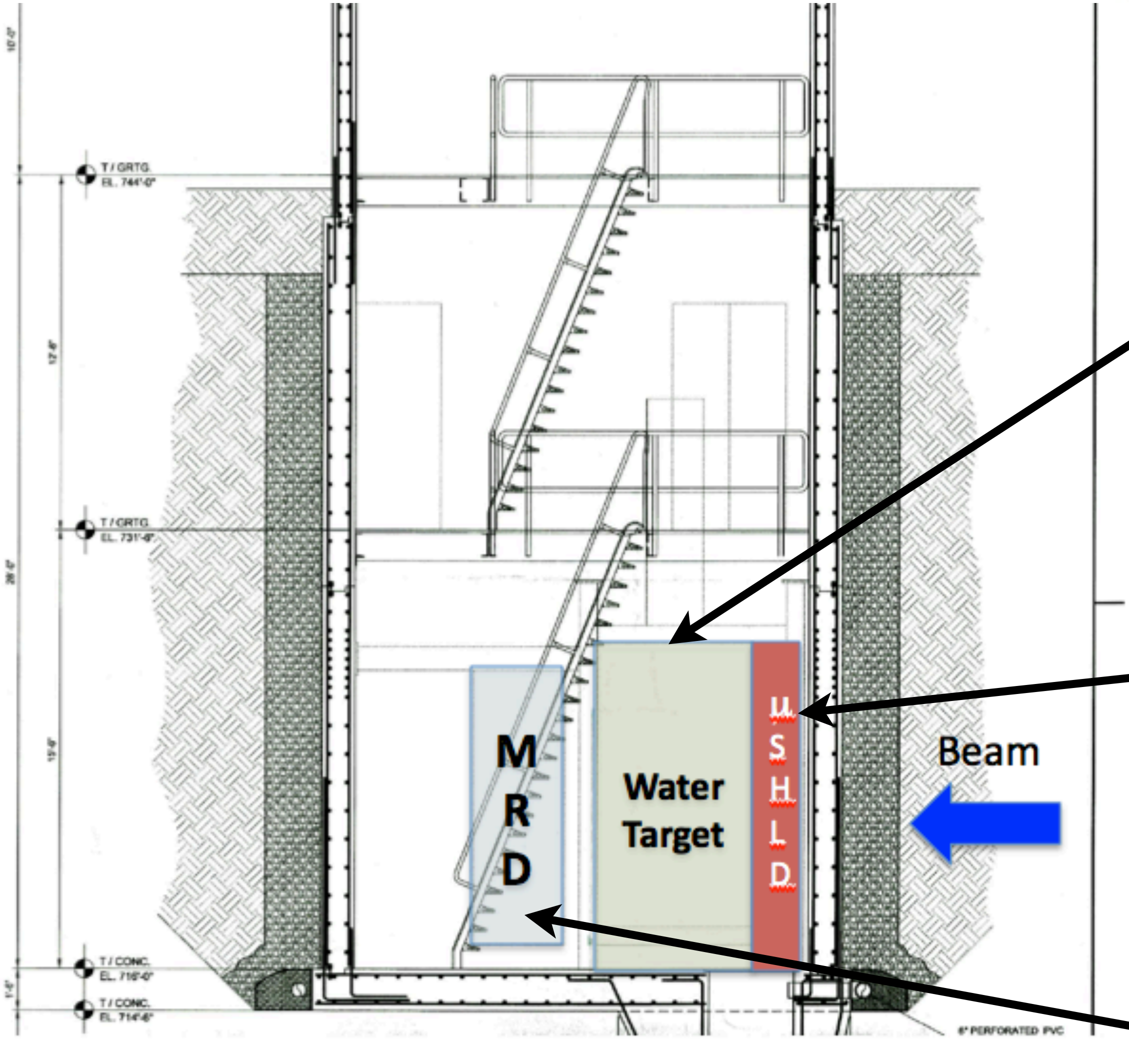
ANNIE Concept



Prompt muon tracks through water volume, ranges in MRD

neutrons thermalize and stop in water

neutrons capture on Gd, flashes of light are detected



3m x 3m x 3m tank of Gd enhanced water instrumented with photosensors.

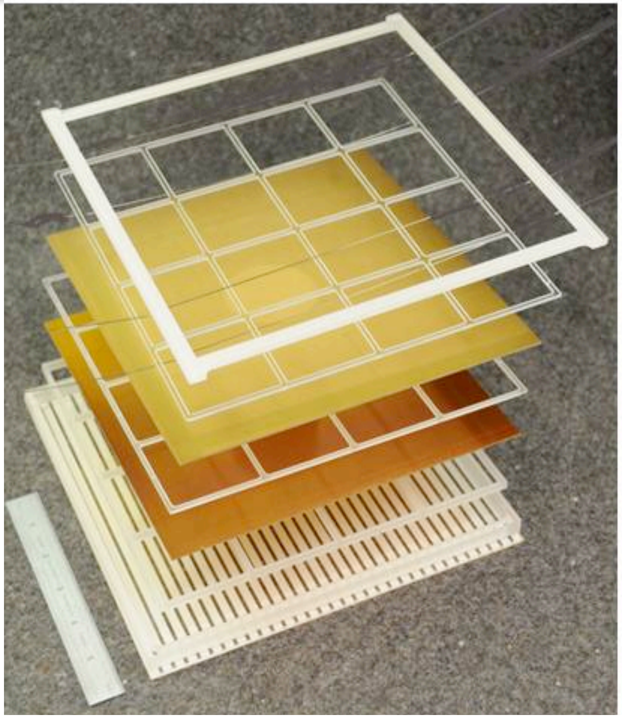
veto on muons produced upstream of the detector (FACC)

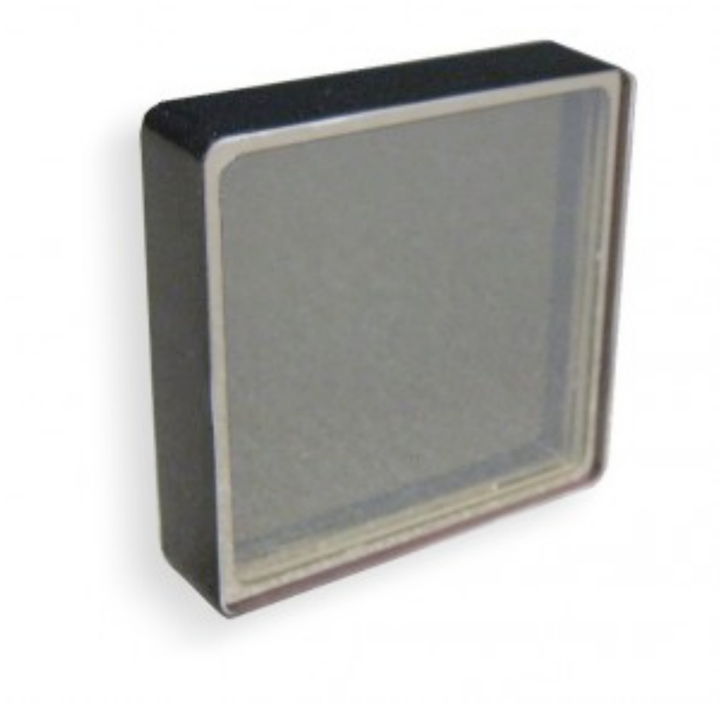
Existing Muon Range Detector (MRD)

“ANNIE Hall”

(formerly the SciBooNE pit)

More on LAPPDs





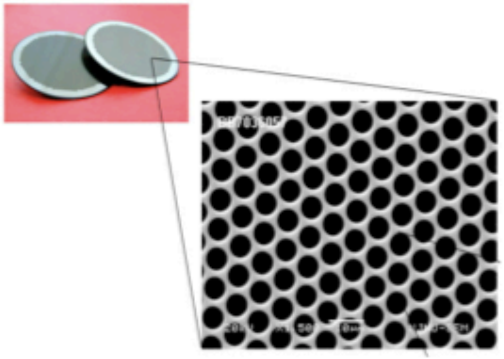
LAPPD detectors:

- Thin-films on borosilicate glass
- Glass vacuum assembly
- Simple, pure materials
- Scalable electronics
- Designed to cover large areas

Conventional MCPs:

- Conditioning of leaded glass (MCPs)
- Ceramic body
- Not designed for large area applications

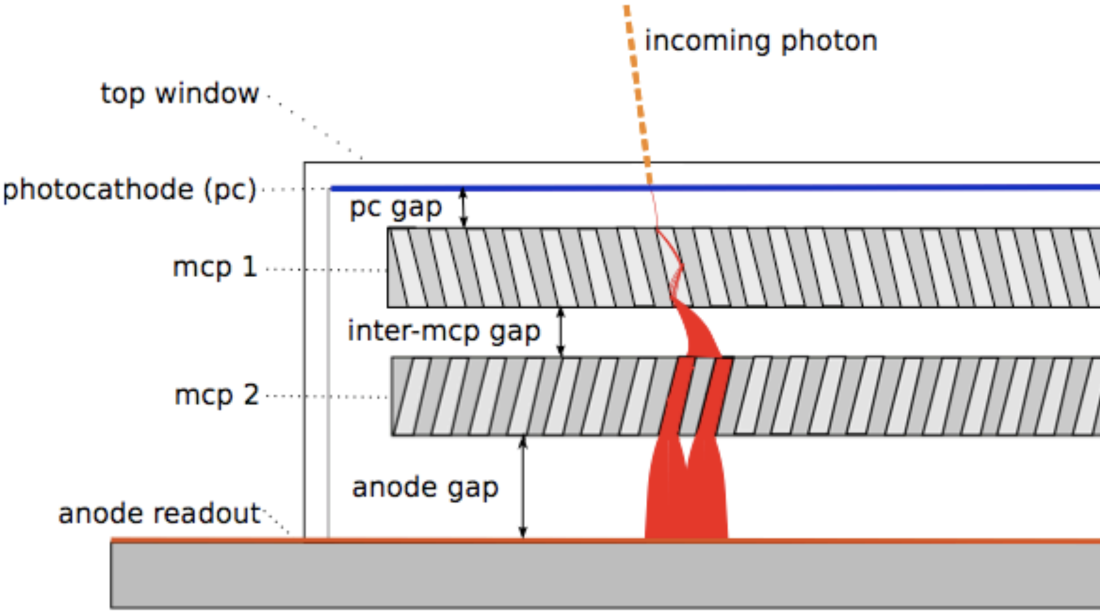
What is an MCP-PMT?



Microchannel Plate (MCP):

- a thin plate with microscopic (typically <50 μm) pores
- pores are optimized for secondary electron emission (SEE).
- Accelerating electrons accelerating across an electric potential strike the pore walls, initiating an avalanche of secondary electrons.

- An MCP-PMT is, sealed vacuum tube photodetector.
- Incoming light, incident on a photocathode can produce electrons by the photoelectric effect.
- Microchannel plates provide a gain stage, amplifying the electrical signal by a factor typically above 10^6.
- Signal is collected on the anode

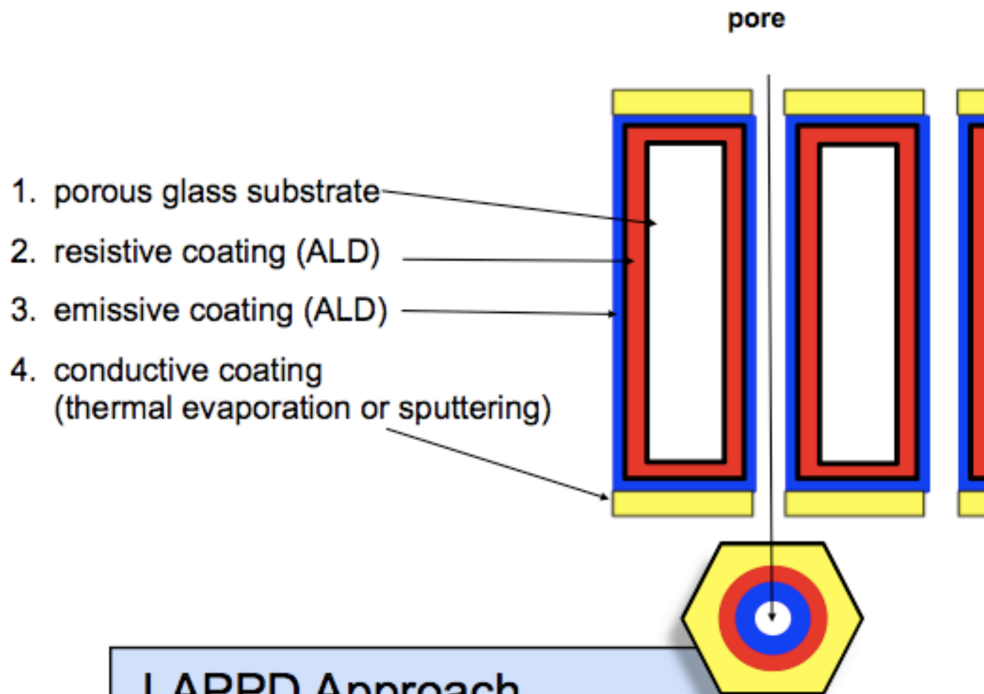


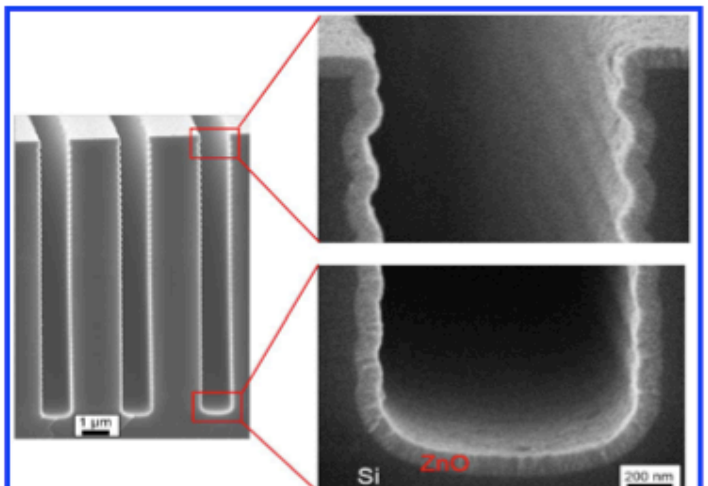
Our Approach

J. Elam, A. Mane, Q. Peng (ANL-ESD),
N. Sullivan (Arradiance), A. Tremsin (Arradiance, SSL)

Conventional MCP Fabrication

- Pore structure formed by drawing and slicing lead-glass fiber bundles. The glass also serves as the resistive material
- Chemical etching and heating in hydrogen to improve secondary emissive properties.
- Expensive, requires long conditioning, and uses the same material for resistive and secondary emissive properties. (Problems with thermal run-away).





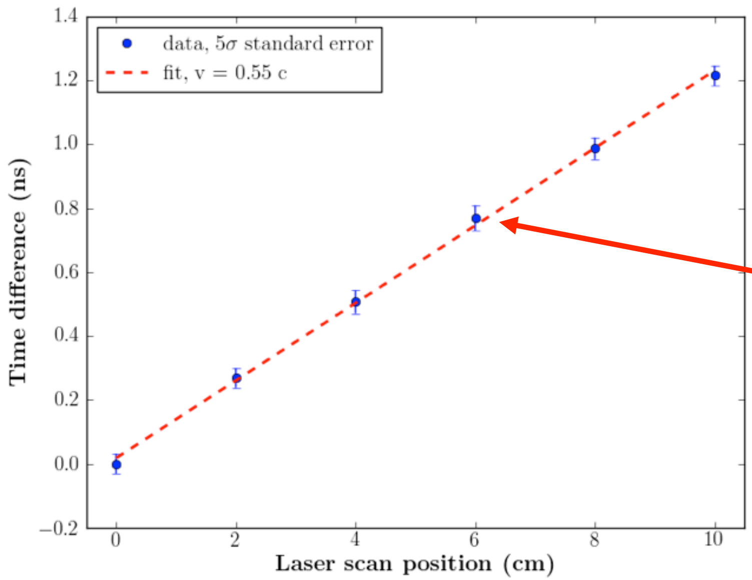
LAPPD Approach

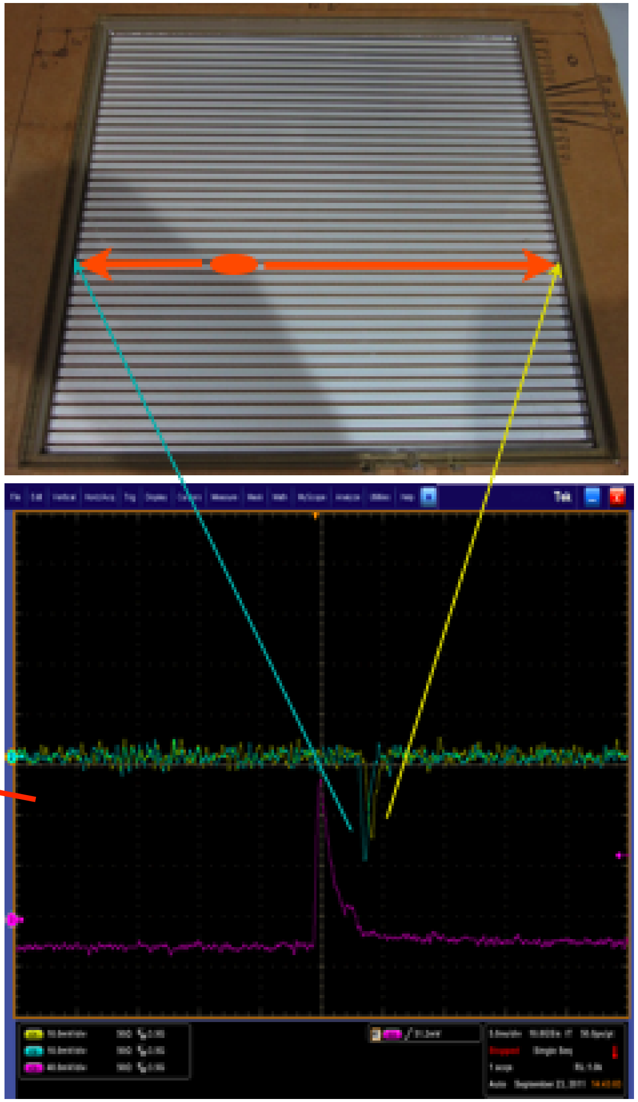
- Separate out the three functions
- Hand-pick materials to optimize performance.
- Use Atomic Layer Deposition (ALD): a cheap industrial batch method.
  - ALD is diffusive, conformal and allows application of material in single atomic monolayers

Anode Design: Delay Lines

Channel count (costs) scale with length, not area
Position is determined:

- by charge centroid in the direction perpendicular to the striplines
- by differential transit time in the direction parallel to the strips



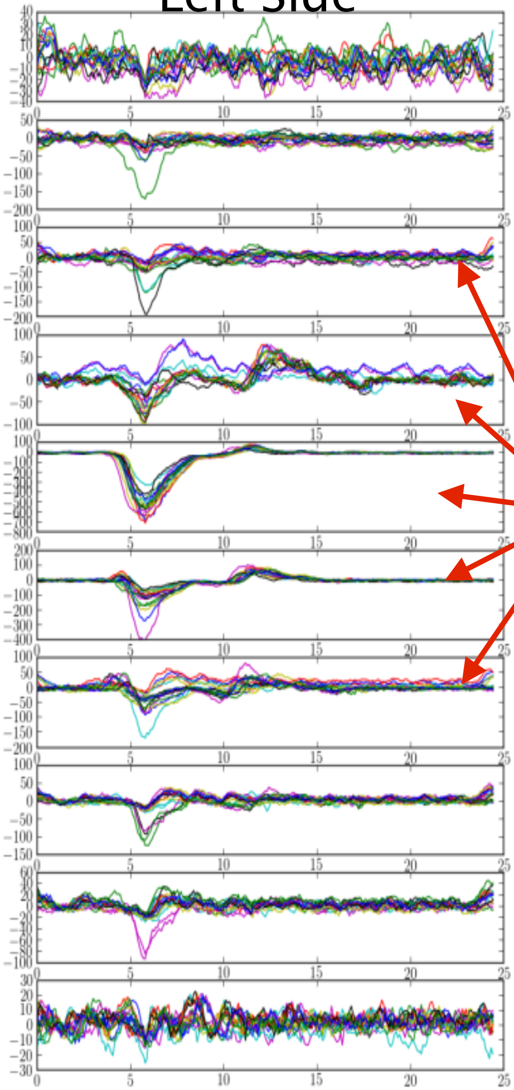


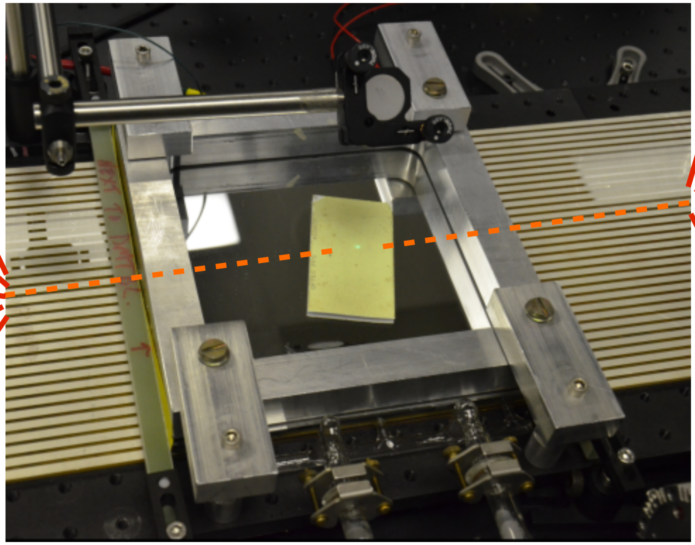
Slope corresponds to ~2/3 c propagations speed on the microstrip lines. RMS of 18 psec on the differential resolution between the two ends: equivalent to roughly 3 mm

Anode design

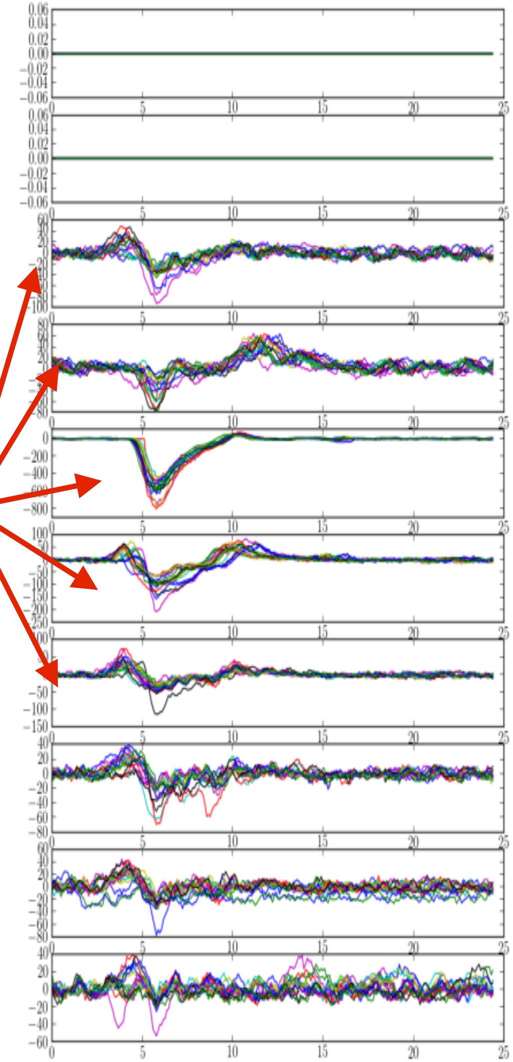
Transverse position is determined by centroid of integrated signal on a cluster of striplines.

Pulses on 10 striplines
Left Side





Credit: Eric Oberla

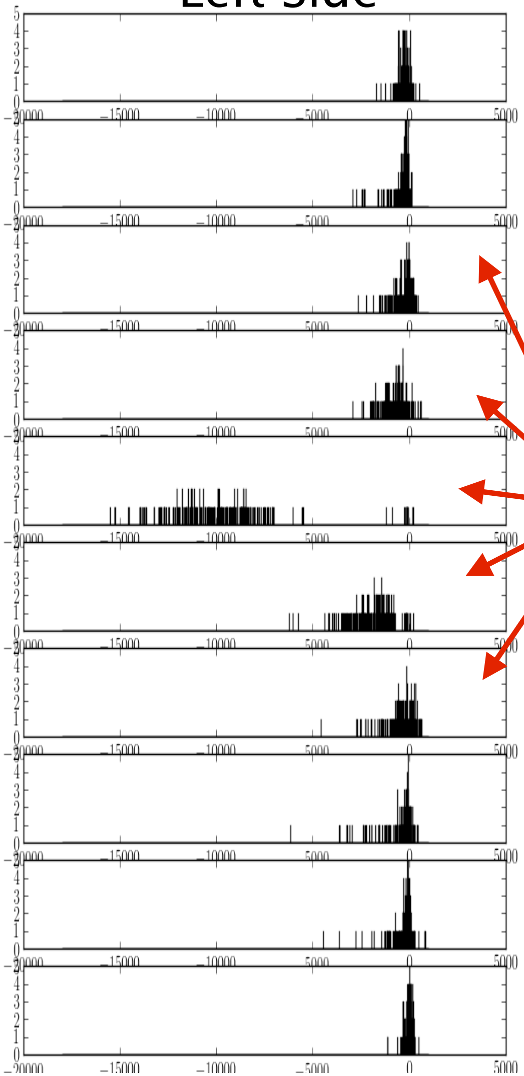


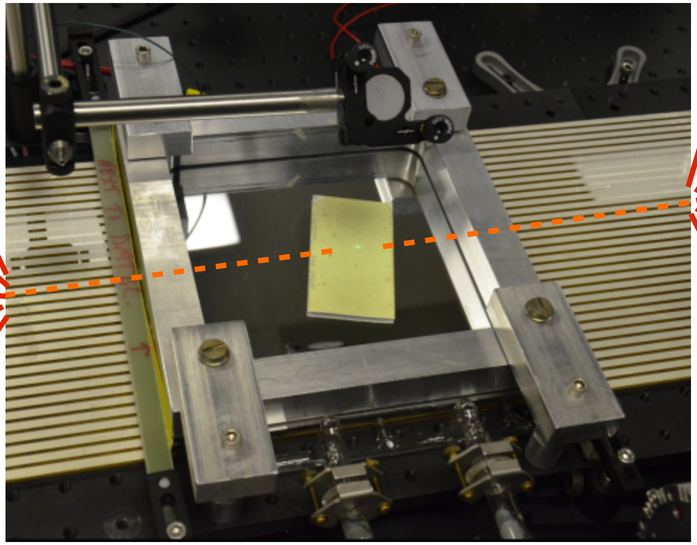
Right Side
Pulses on 10 striplines

Anode design

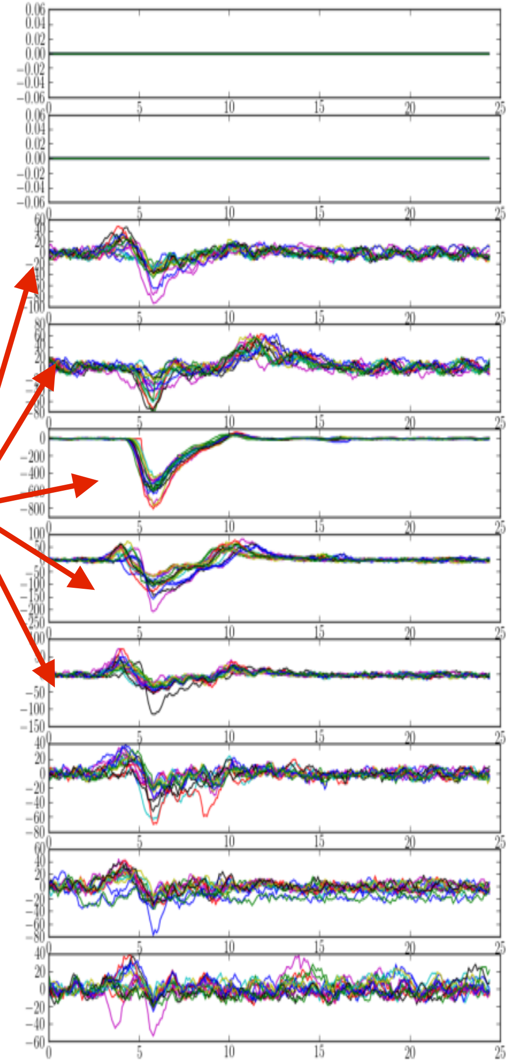
Transverse position is determined by centroid of integrated signal on a cluster of striplines.

Pulse Heights (ADC counts)
Left Side



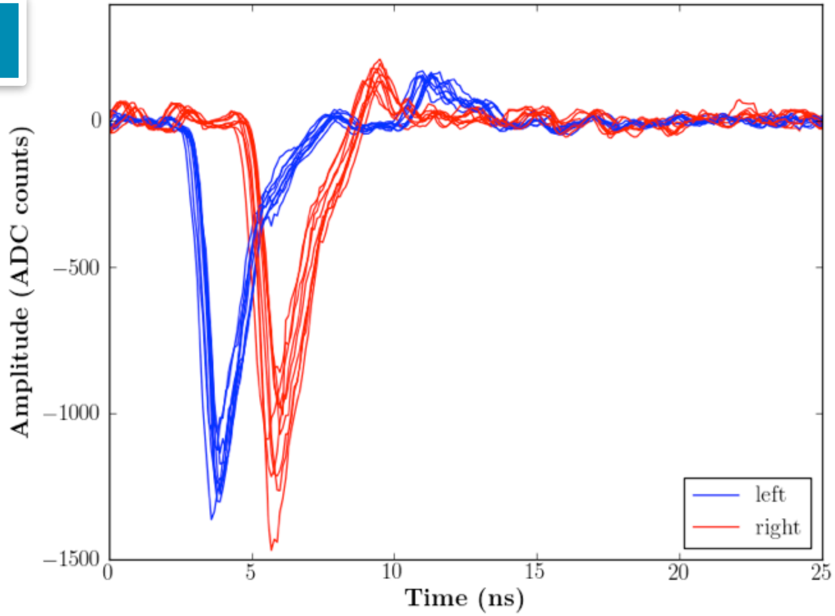


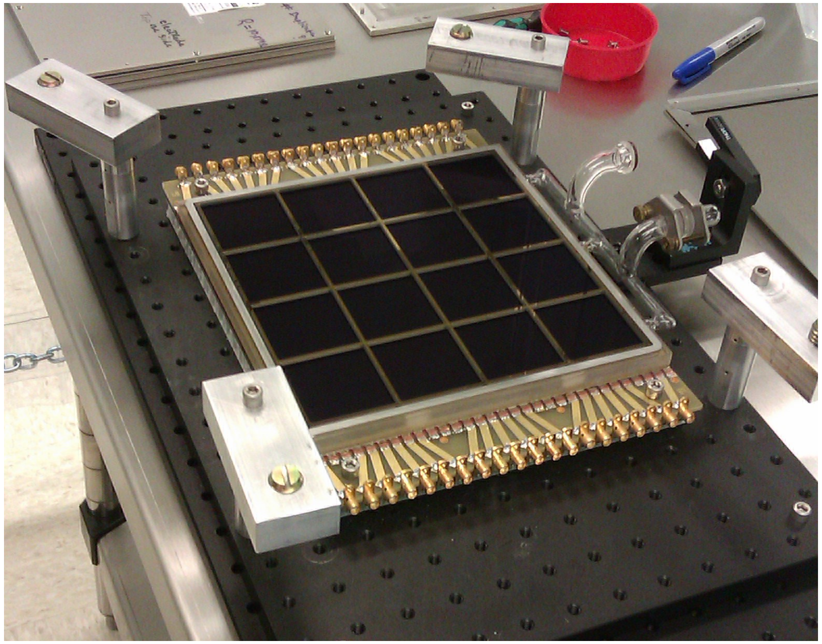
Credit: Eric Oberla



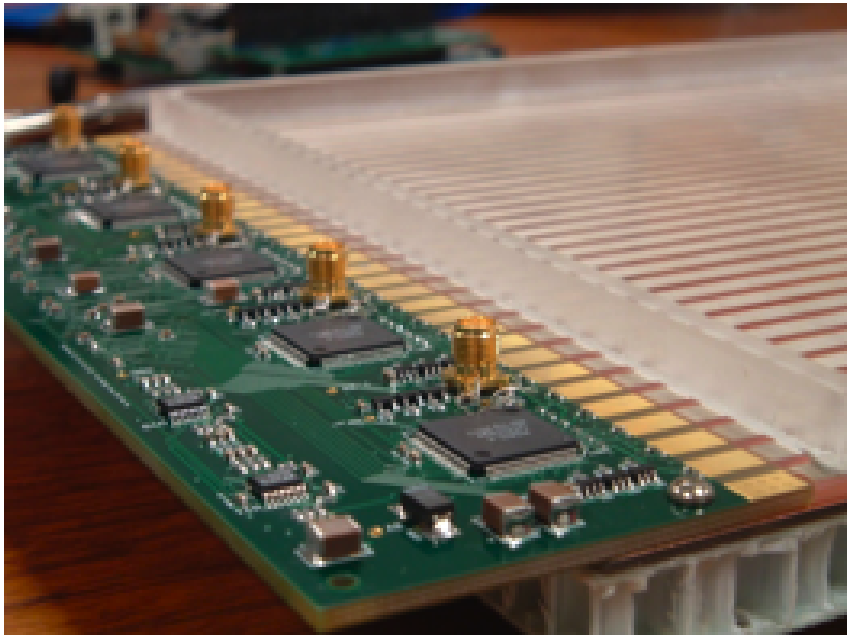
Right Side
Pulses on 10 striplines

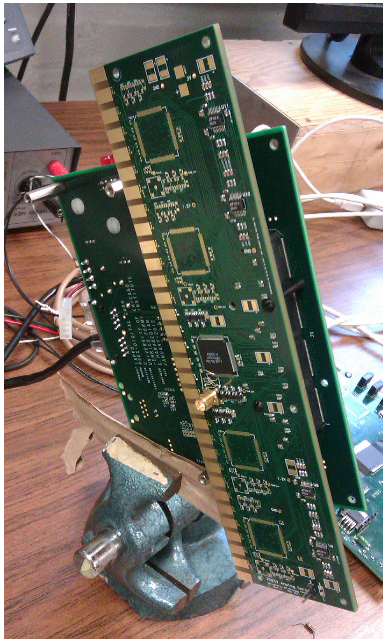
LAPPD





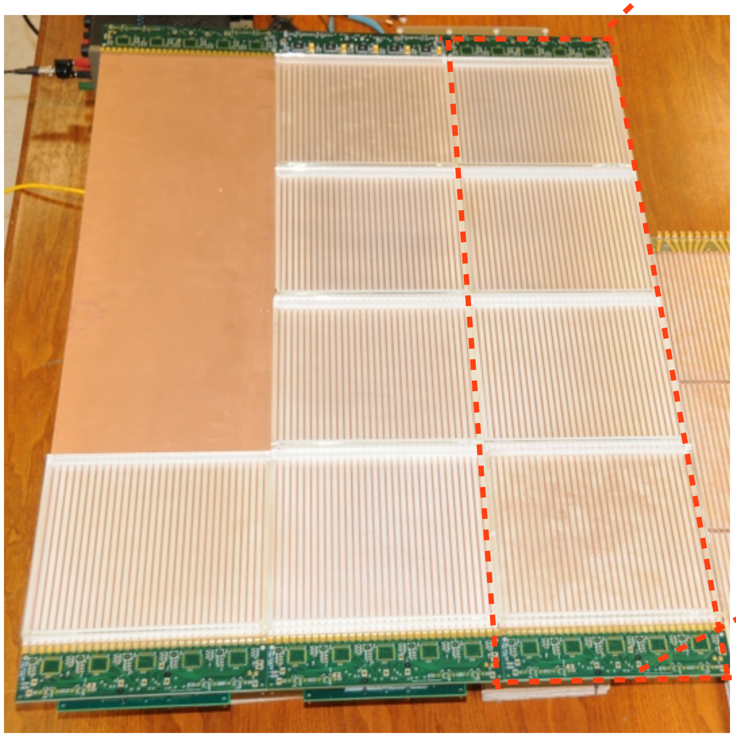
- LAPPD Goal of building a **complete detector system**, including even waveform sampling front-end electronics
- Now testing near-complete glass vacuum tubes ("demountable detectors") with resealable top window, robust aluminum photocathode

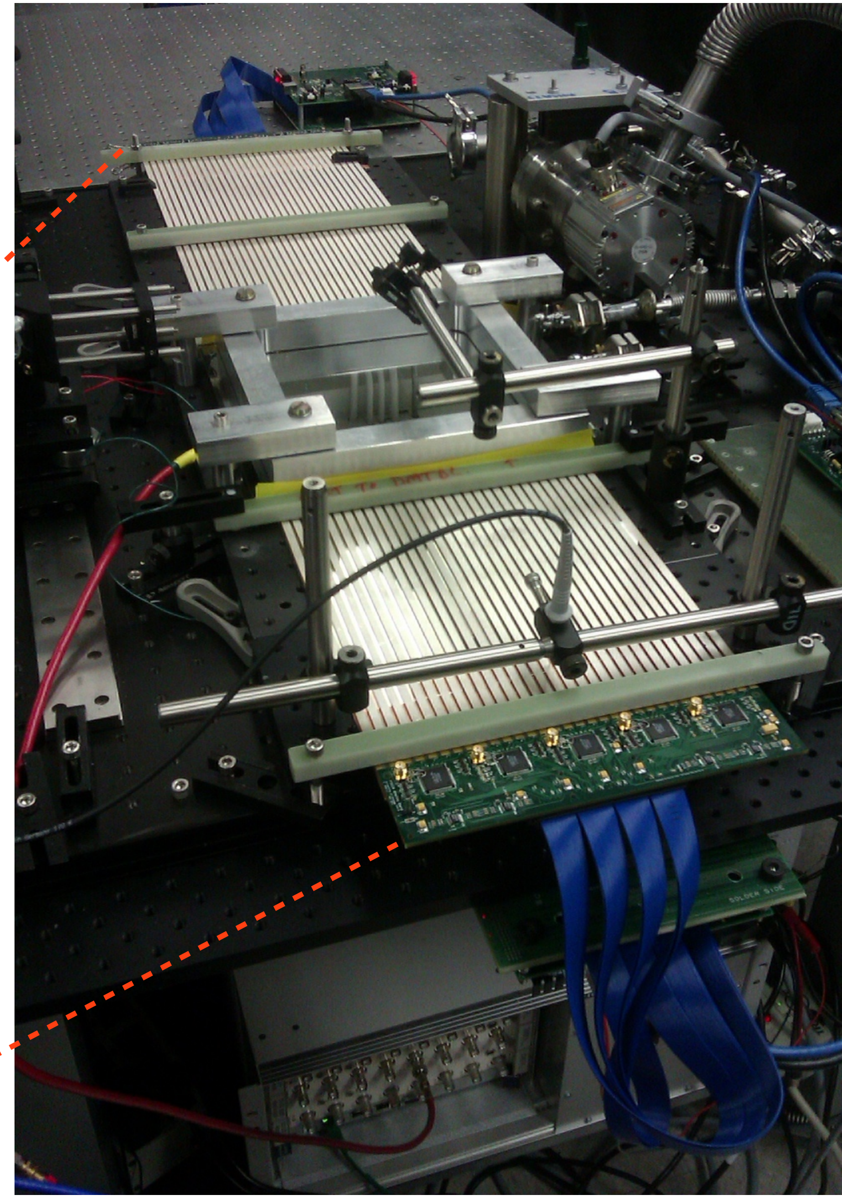




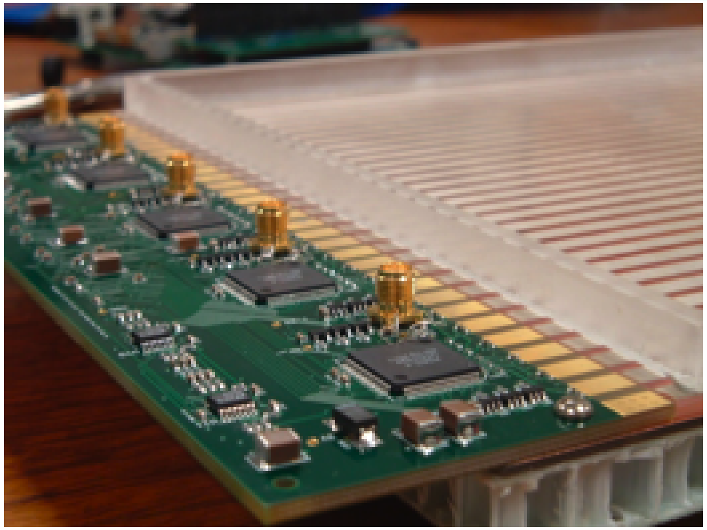
"SuMo Slice"

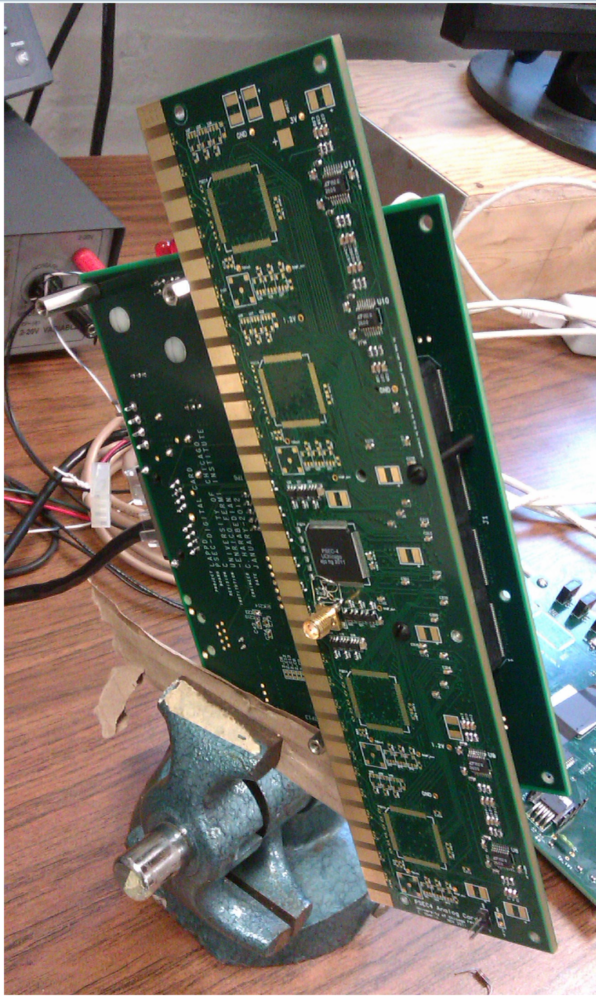
We are now testing a functional demountable detector with a complete 80 cm anode chain and full readout system ("SuMo slice").





Front-end Electronics





Psec4 chip:

- CMOS-based, waveform sampling chip
- 17 Gsamples/sec
- ~1 mV noise
- 6 channels/chip

Analog Card:

- Readout for one side of 30-strip anode
- 5 psec chips per board
- Optimized for high analog bandwidth (>1 GHz)

Digital Card:

- Analysis of the individual pulses (charges and times)

Central Card:

- Combines information from both ends of multiple striplines

Full Track Reconstruction: A TPC Using Optical Light?

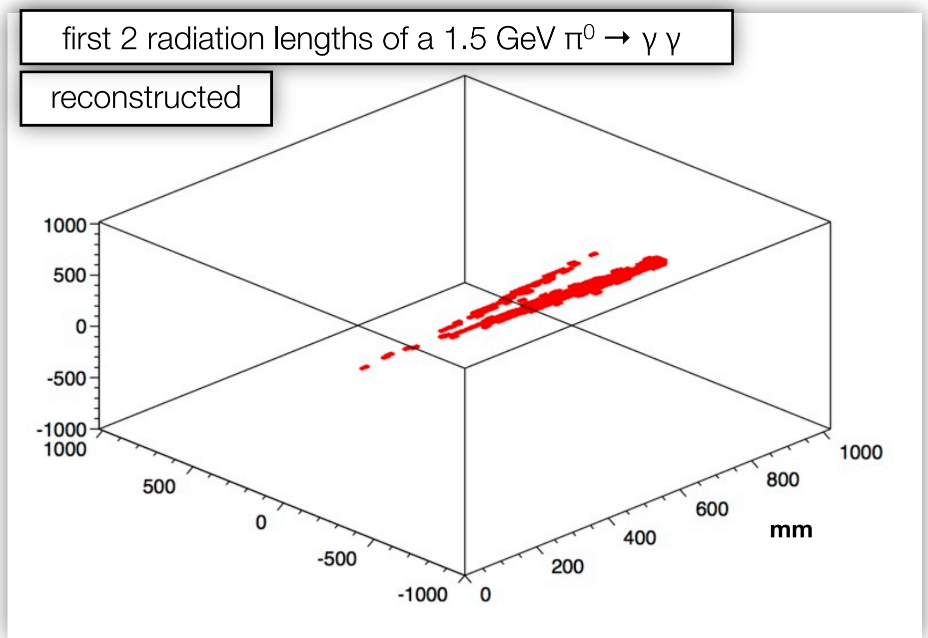


Image reconstruction, using a causal "Hough Transform" (isochron method)

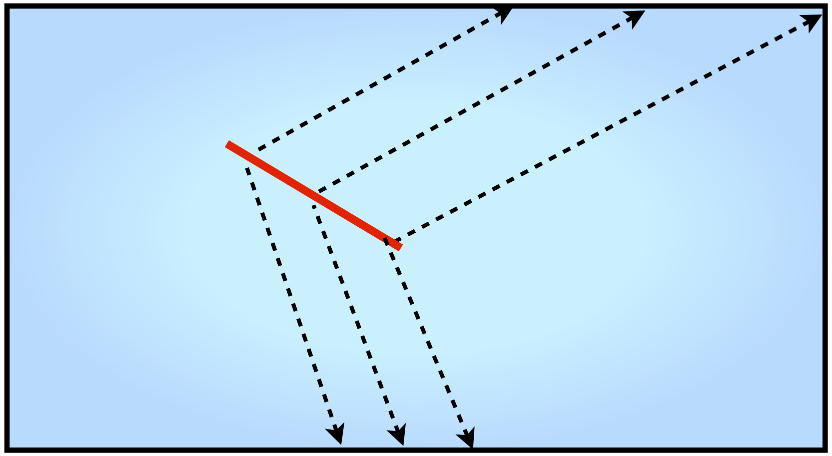
(see ANT13 LAPPD talk)

(see ANT13 mTC talk)

"Drift time" of photons is fast compared to charge in a TPC!

~225,000mm/microsecond

Need fast timing and new algorithms



Full Track Reconstruction: A TPC Using Optical Light?

1. Signal per unit length (before attenuation)

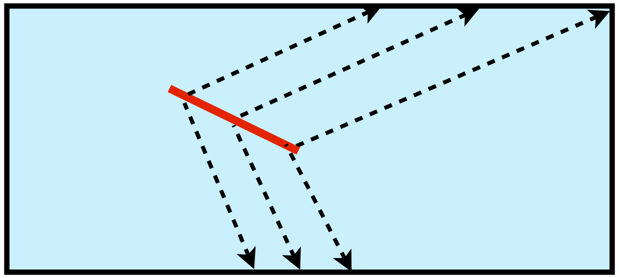
   ~20 photons/mm (Cherenkov)

2. "Drift time" (photon transit time)

   ~225,000mm/microsecond

3. Topology

   drift distances depend
   on track parameters



4. Optical Transport of light in water

Full Track Reconstruction: A TPC Using Optical Light?

1. Signal per unit length (before attenuation)

~20 photons/mm (Cherenkov)

Acceptance and coverage are important, especially at Low E. Is there any way we can boost this number? Scintillation? Chemical enhancement

2. "Drift time" (photon transit time)

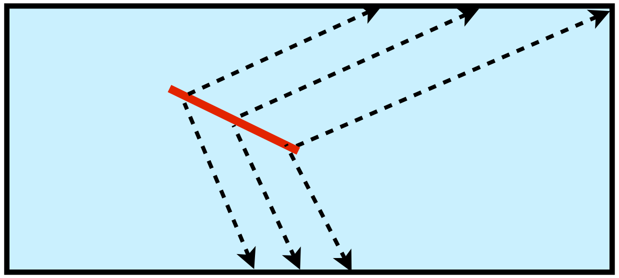
~225,000mm/microsecond

This necessitates **fast** photodetection. It also requires **spatial resolution commensurate with the time resolution.**

3. Topology

drift distances depend on track parameters

This presents some reconstruction challenges, but not unconquerable.

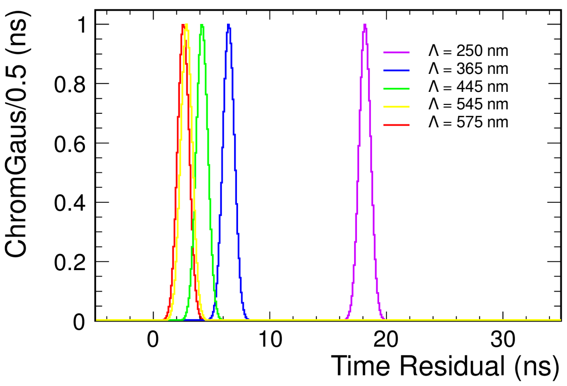


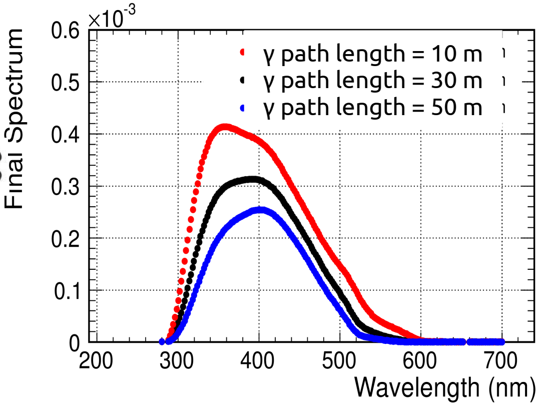
4. Optical Transport of light in water

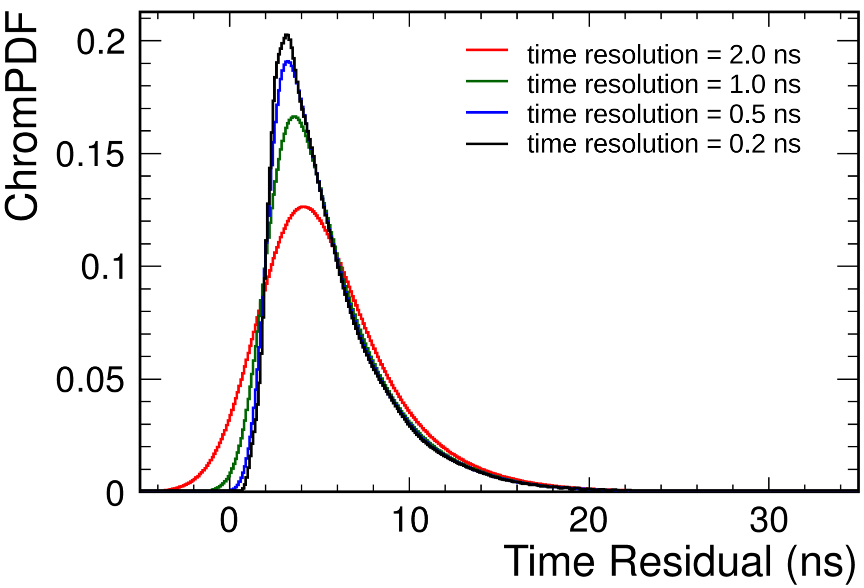
Appropriate reconstruction techniques are needed.

"Simple Vertex" Reconstruction

- A timing residual-based fit, assuming an extended track.
- Model accounts for effects of chromatic dispersion and scattering.
  - separately fit each photon hit with each color hypothesis, weighted by the relative probability of that color.
- For MCP-like photon detectors, we fit each photon rather than fitting (Q,t) for each PMT.
- Likelihood captures the full correlations between space and time of hits
- Not as sophisticated as full pattern-of-light fitting, but in local fits, all tracks and showers can be well-represented by simple line segments on a small enough scale.







Work by I. Anghel, M. Sanchez, M Wetstein, T. Xin

“Simple Vertex” Reconstruction

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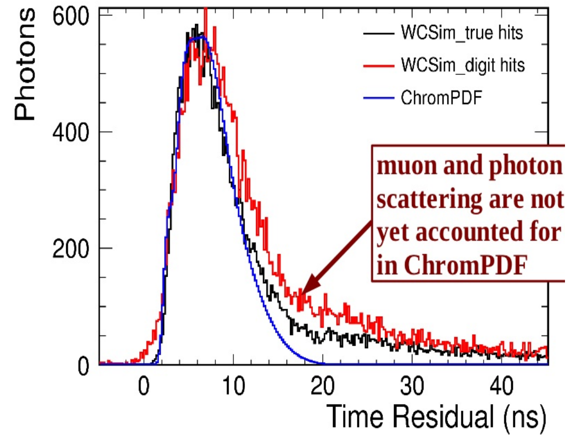
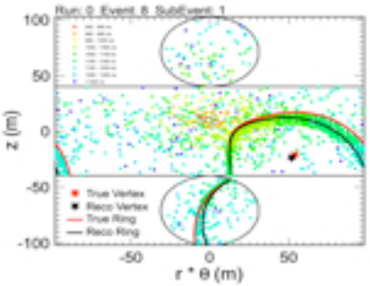
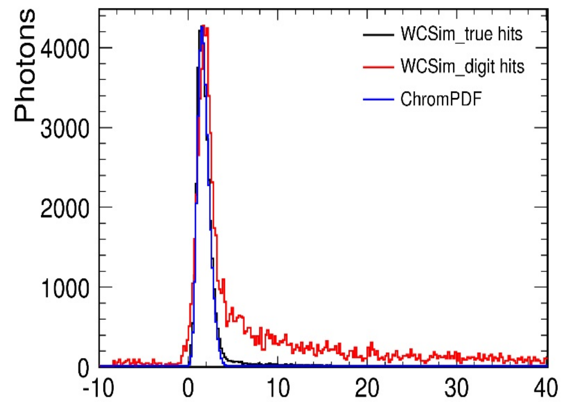
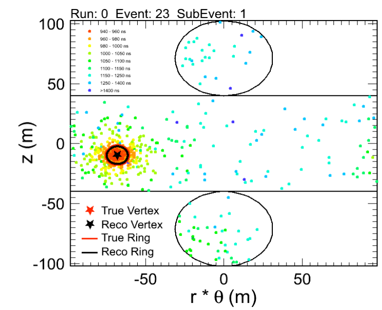
- Likelihood captures the full correlations between space and time of hits
- Not as sophisticated as full pattern-of-light fitting, but in local fits, all tracks and showers can be well-represented by simple line segments on a small enough scale.







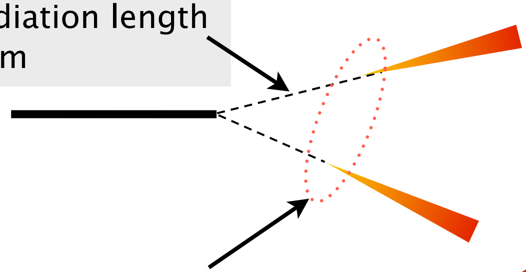


Work by I. Anghel, M. Sanchez, M Wetstein, T. Xin

Simple Vertex Reconstruction

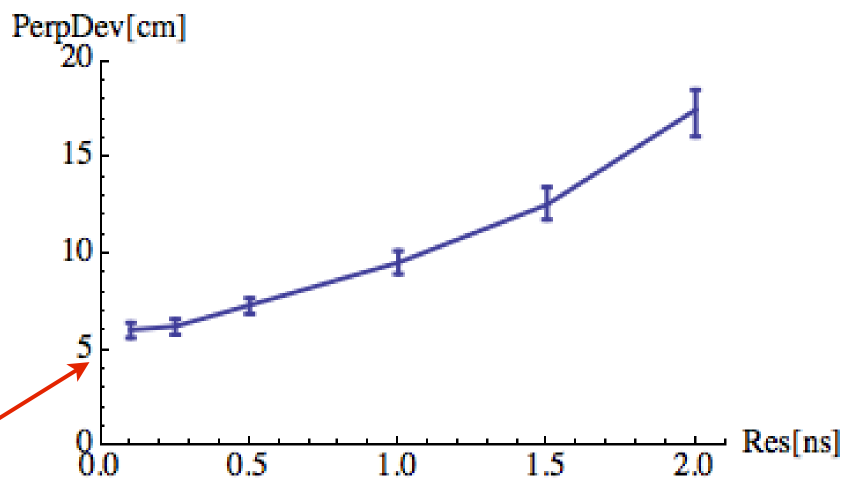
- Transverse component of the vertex (wrt to track direction) is most sensitive to pure timing since T0 is unknown.
- Separating between multiple vertices depends on differential timing (T0 is irrelevant)
- We study the relationship between vertex sensitivity and time resolution using GeV muons in water. This study is performed using the former LBNE WC design, with 13% coverage and varying time resolution.
- Transverse vertex reconstruction is better than 5 cm for photosensor time resolutions below 500 picoseconds.

~1 radiation length
~37 cm



vertices are separated:
at 7 degrees: ~4.5 cm
at 15 degrees: ~9.7 cm

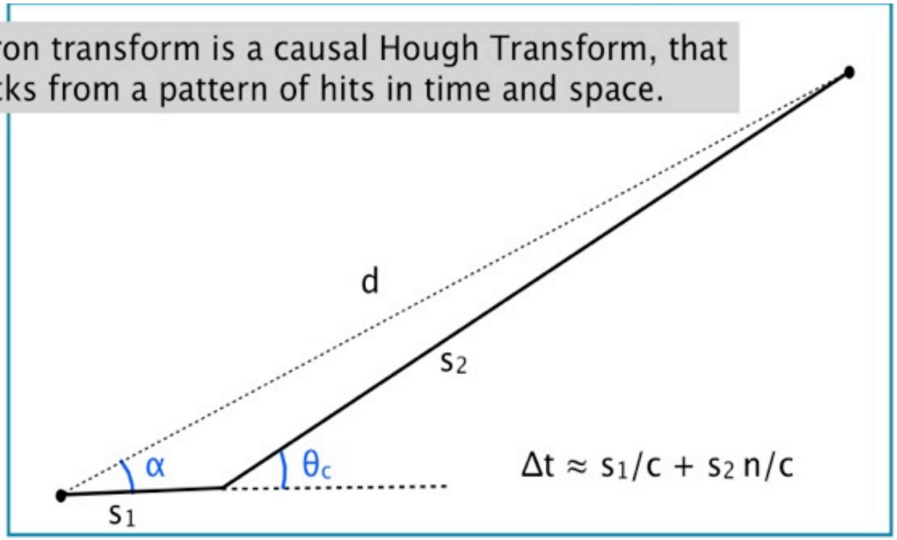
Optical TPCs are scalable to 100s of kilotons



Work by I. Anghel, M. Sanchez, M Wetstein, T. Xin

Isochron

The isochron transform is a causal Hough Transform, that builds tracks from a pattern of hits in time and space.



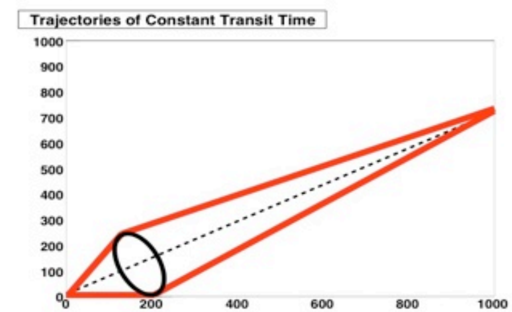
Connect each hit to the vertex, through a two segment path, one segment representing the path of the charged particle, the other path representing the emitted light. There are two unknowns:

s_1 and α

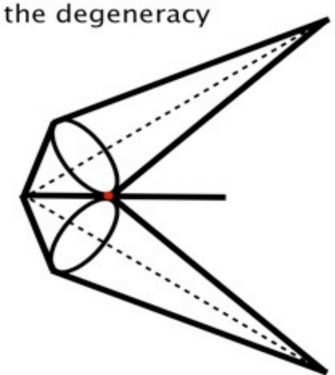
but there are two constraints:

$s_1 + s_1 = d$ and $\Delta t_{measured} = s_1/c + s_2\, n/c$

For a single PMT, there is a rotational degeneracy (many solutions).

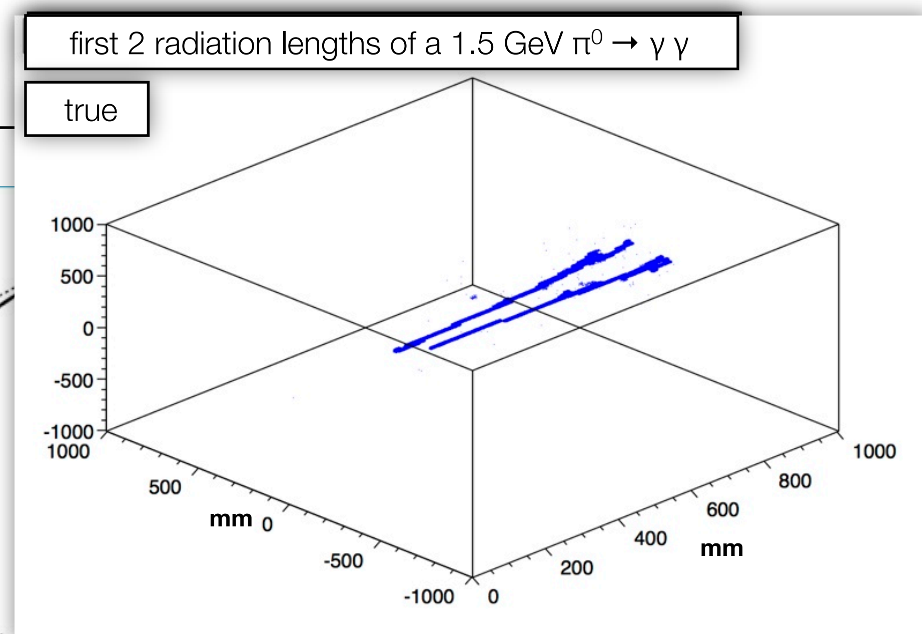


But, multiple hits from the same track will intersect maximally around their common emission point, resolving the degeneracy



M. Wetstein

Isochron



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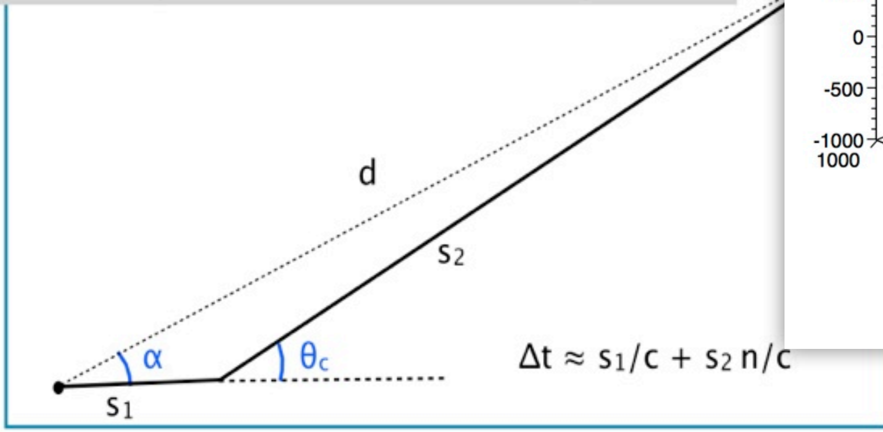

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M. Wetstein

Isochron

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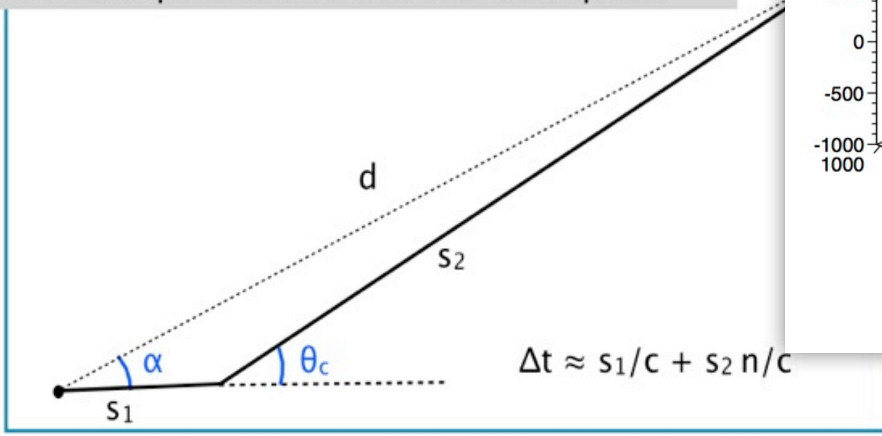

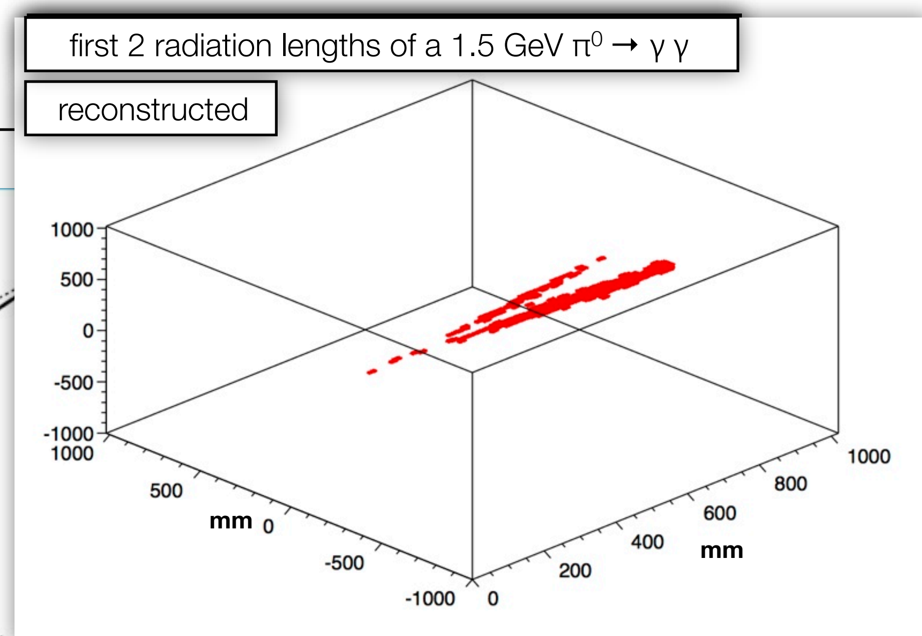

Connect each hit to the vertex, through a two segment path, one segment representing the path of the charged particle, the other path representing the emitted light. There are two unknowns:

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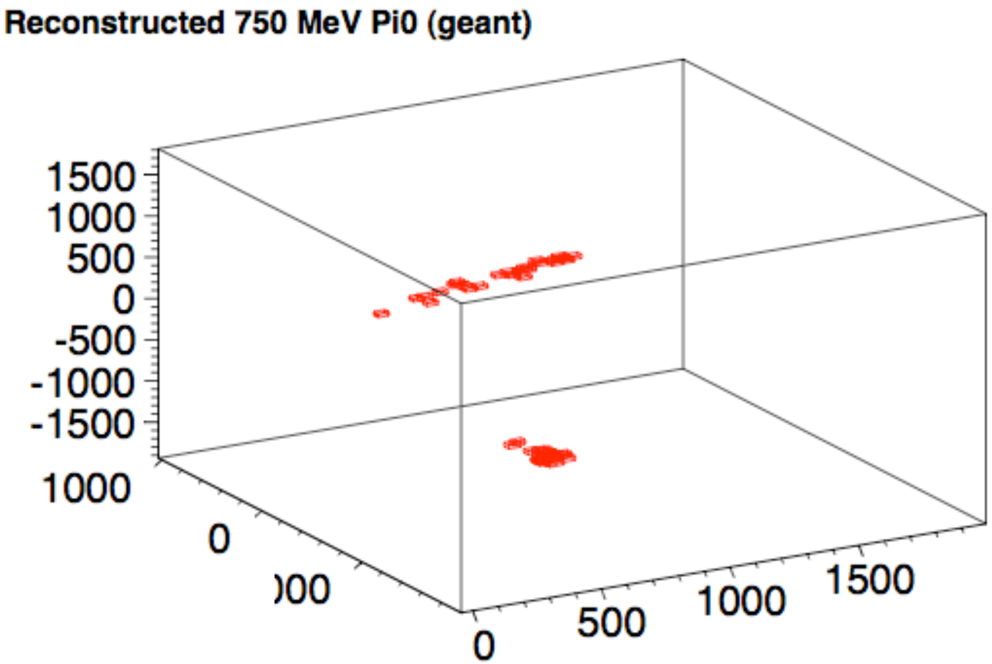
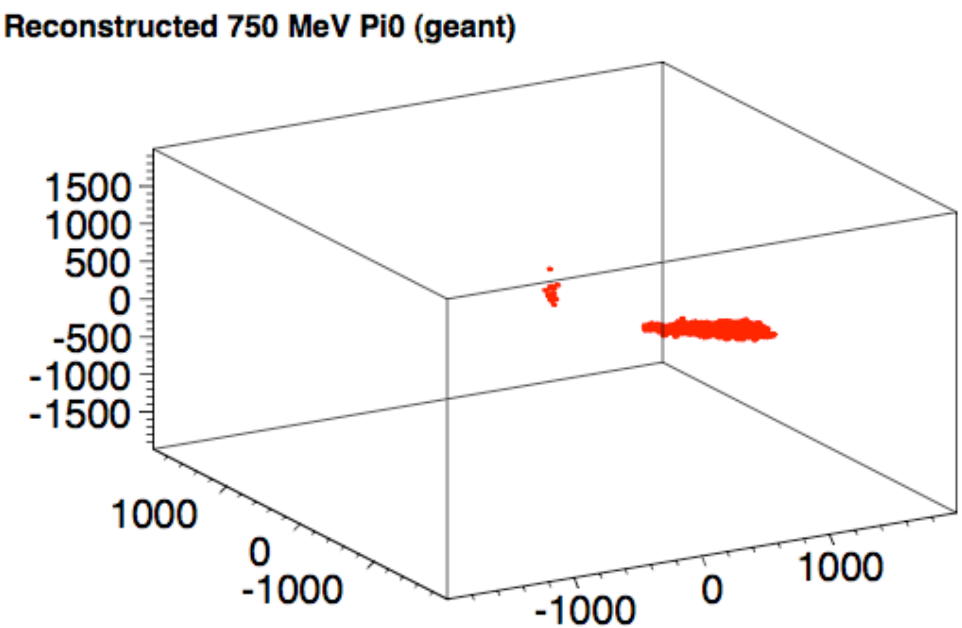
$s_1 + s_1 = d$ and $\Delta t_{measured} = s_1/c + s_2\, n/c$

Could be useful for full pattern-fitting approached by providing a seed topology and restricting the phase space of the fit.

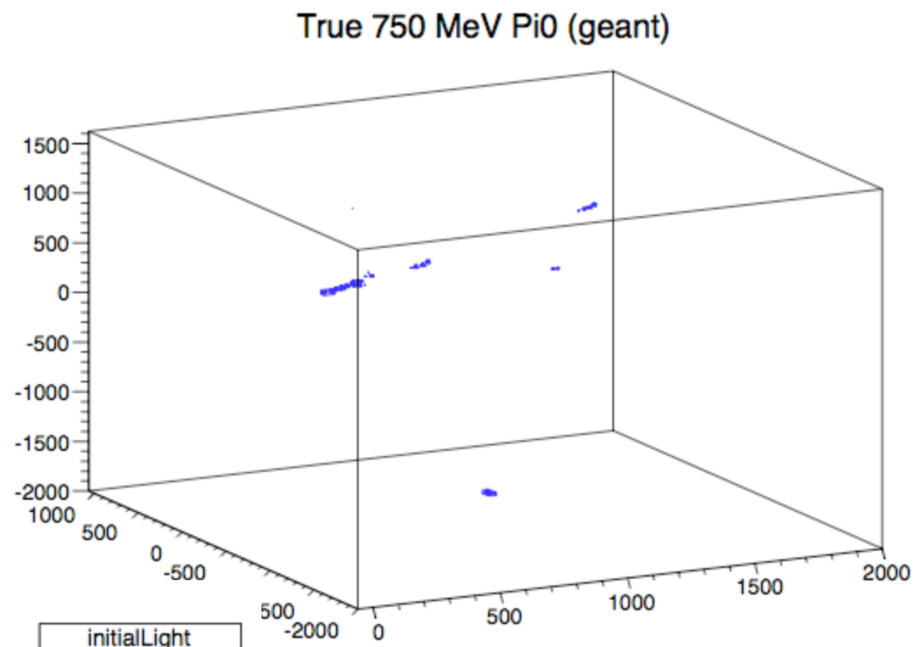
M. Wetstein

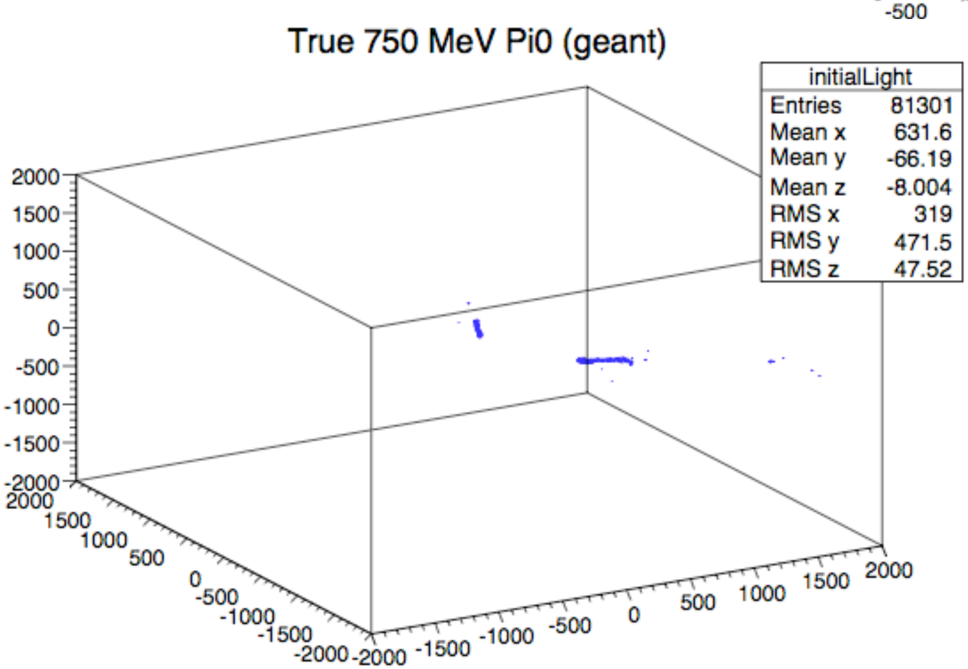
Comparing Isochron Reconstruction with Truth



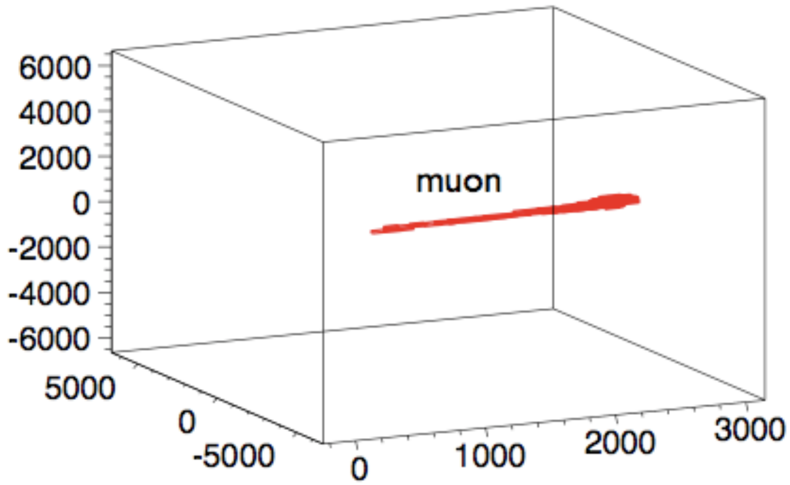


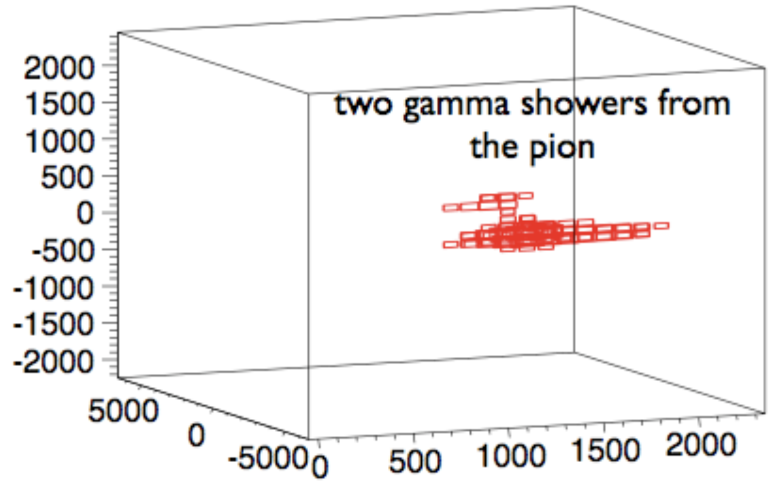
Comparing Isochron Reconstruction with Truth

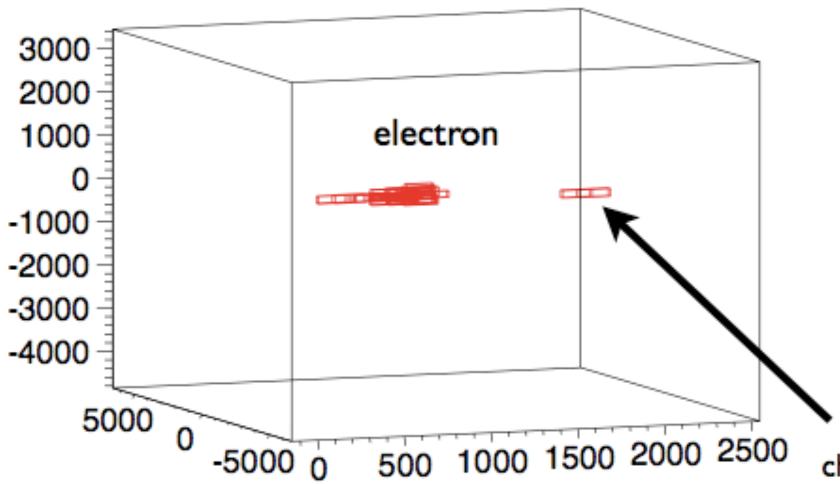




Reconstructing Geant Events





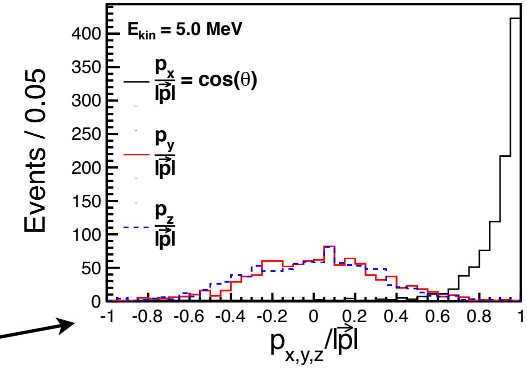


check out the detached shower from the bremstrahlung!!

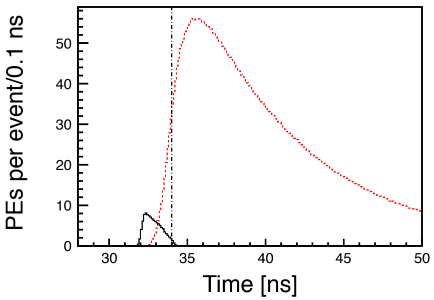
Optical TPC with scintillator

Optical TPC concept is more general than pure Cherenkov.

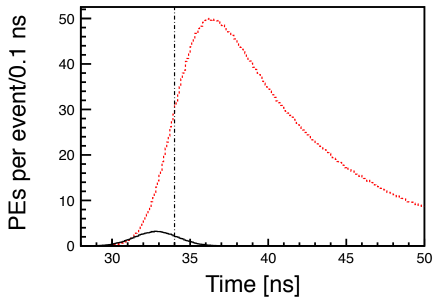
It may be possible to use timing to separate between Cherenkov and scintillation light in liquid scintillator volumes, capitalizing of the advantages of each separately.



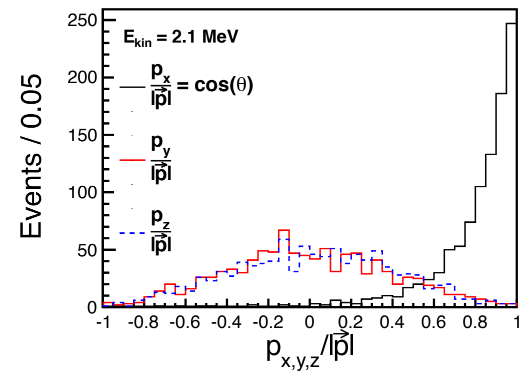
One can use the scintillation light for low E sensitivity. <u>And the Cherenkov light for directionality</u>.

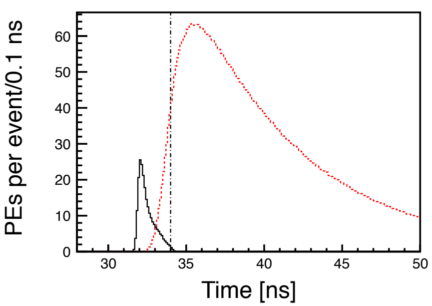


(a) Default simulation.



(b) Increased TTS (1.28 ns).





(c) Red-sensitive photocathode.

C. Aberle, A. Elagin, H.J. Frisch, M. Wetstein, L. Winslow. Measuring

Directionality in Double-Beta Decay and Neutrino Interactions with Kiloton-Scale Scintillation Detectors;

Submitted to JINST, Nov. 2013. e-Print: arXiv:1307.5813